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SCIENCE NEWS BY AGU

Predicting Dust Storms

Exoplanet Earth

Citing Data Sets

ADVANCING FOOD SECURITY THROUGH GEOSCIENCE

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Our Place in the Food Security Chain

Food insecurity is a growing threat in many places around the world. This situation is exacerbated by two events that many geoscientists are tasked to study: natural hazards and our changing climate. In this issue of *Eos,* we look at how geoscientists are using their research to help create resilient communities around the world that can always be sure of food in their pantries.

"Food security is an issue that resonates with all of us—it's a grand challenge across regions and spatial and temporal scales," said Ben Zaitchik of Johns Hopkins University in Baltimore, Md. "We want to highlight the ways in which geoscientists can contribute to meeting this challenge." Zaitchik is the *Eos* science adviser from AGU's GeoHealth section who helped us develop this issue along with Merritt Turetsky, our Biogeosciences science adviser at the University of Colorado Boulder.

"As the geosciences start to grapple deeply with issues of environmental and social justice, there is no better exemplar than the food we eat and the water we drink," said Turetsky. "Crop production, labor markets, water rights across the urban-agricultural divide: These are all issues that society needs to face and in which the geosciences have a strong role to play."

In "Sowing Seeds of Food Security in Africa" (p. 28), Catherine Nakalembe and colleagues discuss their work at NASA Harvest Africa and how they strive to improves the lives of smallholder farmers by using satellite technology to harness data and guide agricultural decision-making. Nakalembe, the program director, was recently named a 2020 Africa Food Prize Laureate for her service in this area, and we are honored to feature her team's work in this issue.

We dive deeper into the opportunities for satellite data to contribute to these efforts with M. E. Brown, a research professor with the University of Maryland, on page 17. "I found the diversity of organizations involved in geoscience applications to food security in the developing world to be energizing," said Zaitchik of Brown's analysis of the current state of food security initiatives. "The fact that international research partnerships are working directly with national ministries in food-insecure regions, and that small business start-ups in developing countries are working with advanced geoscience techniques, is really quite exciting."

Finally, we take a broader look at food security in "Climate Change Uproots Global Agriculture" on page 34. A warming world is bringing inexorable changes to ecosystems. In many places, a crop that thrived just a few decades ago no longer survives in the climate that exists there today. Geoscientists play a crucial role in understanding what the future is going to look like and how farmers can adapt.

"Geospatial analyses, development of new geotechnical skills, and improved understanding of ecohydrology and biogeochemistry will become even more important for what we eat and how we eat in the future," added Turetsky. "Food and water distributions will increasingly become a STEM issue as well as an environmental and social justice issue."

We thank all of the geoscientists who are contributing solutions to the serious challenges threatening food security. We will continue to follow your work and report on it here in the pages of *Eos.*

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

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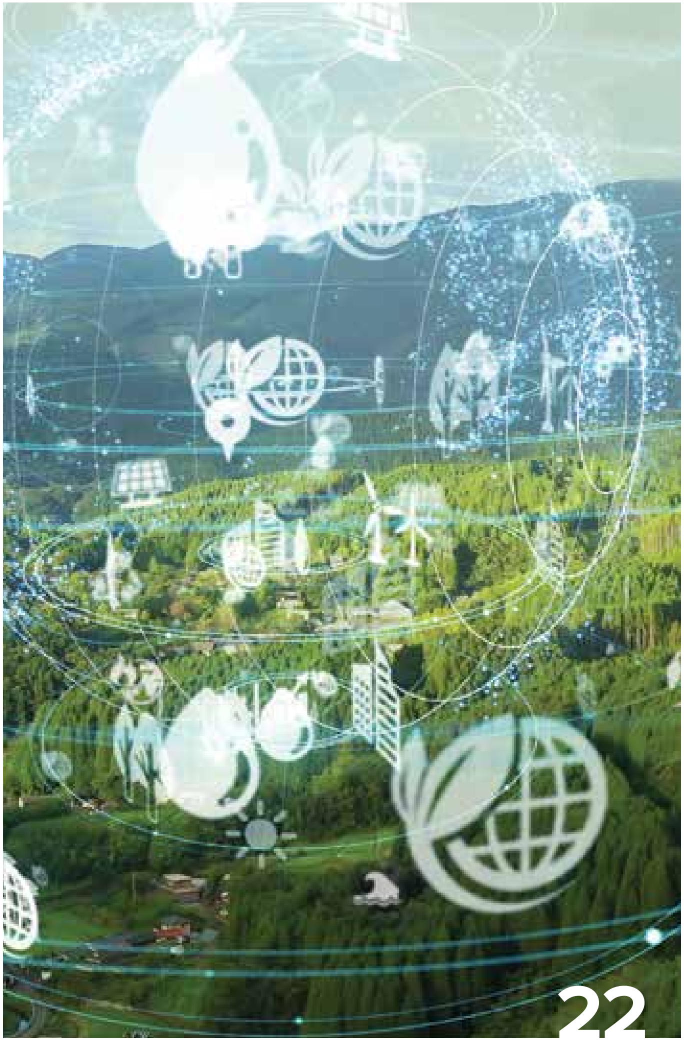

Features

On the Cover

Drip irrigation is one way Kenyan farmers save water to adapt to drought periods due to climate change.
Credit: Joerg Boethling / Alamy Stock Photo

Columns

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Saving Lives by Predicting Dust Storms

Dust storms can reach kilometers wide and thousands of meters tall. They're so thick and form so quickly that they can cut visibility to zero in under a minute. When dust storms strike highways, they make safe driving nearly impossible. These storms can even transport infectious pathogens, like the fungus responsible for valley fever.

Dust storms consist of fine, dry soil particles blown by strong winds, often generated by a thunderstorm. Four main factors for dust storm formation are wind, soil moisture, vegetation cover that can help hold soil in place, and seasonal temperatures. Human activity, like industrial development and agriculture, can also contribute to soil erosion and dusty conditions.

In the American Southwest, accurately predicting these storms has remained a challenge. Daniel Tong, an atmospheric scientist and associate professor at George Mason University, has been working to change that with a new satellite-aided dust forecasting system.

This dust storm, which grew to more than 160 kilometers wide, raged through Arizona in 2011. Credit: Roxy Lopez, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

Predicting the Future

Current meteorological models, like those used by the National Weather Service, don't work well for predicting dust storms in the relatively small region of the southwestern United States. Mariana Casal, division manager of the Pinal County Public Health Department in Arizona, who has worked with Tong on dust-related public health projects, said current alert systems warn of dust storms only about an hour or two in advance.

"Predicting dust is very challenging. Models are not very good at predicting high winds, and you have to capture the precipitation right, which is also difficult to predict. And you have to get the surface conditions right," said Tong. "It's not easy."

Tong and his team are trying to get everything right by using near-real-time satellite imagery. The satellite images can show surface conditions that breed dust storms so that forecasting models can incorporate data on active dust sources.

Providing early warnings could prevent traffic accidents and deaths. Dust storms cut visibility and coat roads in fine particles, making the surface slippery and creating dangerous driving conditions. Tong and his colleagues have looked at police records from the U.S Department of Transportation's Fatality Analysis Reporting System and estimate that dust storms led to traffic accidents that killed between 13 and 33 people each year between 2007 and 2017.

Having a better forecast, even alerting people of what to expect in the morning, afternoon, or night, would be helpful, said Casal. Such a forecast could help people better plan their travel and prevent them from driving right before dust storms.

"That region really needs this kind of work," said Andrea Sealy, chair of the Pan-American Regional Steering Group of the World Meteorological Organization's Sand and Dust Storm Warning Advisory and Assessment System. In the U.S. Southwest, not only can dust storms cause traffic accidents, but they also lower air quality and transport valley fever–causing fungus. "All of these have environmental health and economic consequences," said Sealy.

The Future of Dust Forecasting

So far, Tong thinks the new technique, which he and his team presented at AGU's Fall Meeting 2020, shows promise (bit.ly/dust-storm-forecasting). "We are going to share the information with the National Weather Service so they can adopt the approach," he said.

Tong's team is also working with a dust watch group to get forecasts into the hands of the public. This group consists of high school students working to develop cell phone apps that can warn users of dust storms. But most dust models use data inscrutable to nonexperts. "Our group developed a data service where we put the model's data in our computers and we convert it into a readable format so that people can use our data to build their own apps," said Tong.

Tong's forecasting system, part of a larger project with the Applied Sciences program at NASA, not only will help reduce highway accidents but also could improve disease surveillance for valley fever and air quality management. "If we do things right," said Tong, "then we can save people's lives."

By **Jackie Rocheleau** (@JackieRocheleau), Science Writer

An Ice Core from the Roof of the World

There isn't much room for error 8,000 meters above sea level, and everyone on the expedition knew it. Mount Everest is notoriously challenging to climb, but conducting research on the iconic mountain is an even taller task. In May 2019 that was the task of the National Geographic and Rolex Perpetual Planet Everest Expedition.

It was clear and sunny, but the thin air was bitterly cold. The team relied on supplemental oxygen to breathe. Bundled in brightly colored snowsuits with their faces obscured by ski goggles, the scientists were virtually unrecognizable. They wrote their names on their chests with Sharpies.

The expeditions efforts provided both a model for high-altitude fieldwork and valuable weather data and climate records from Mount Everest. On the expedition, Mariusz Potocki, a Ph.D. student at the University of Maine, collected an ice core from the highest elevation to date. Potocki and his adviser, Paul Mayewski, the expedition's scientific leader, have since begun analyzing the sample using a nondestructive and high-resolution technique called laser ablation. Mayewski spoke at AGU's Fall Meeting 2020 (bit.ly/roof-of-the-world).

Exactly what they'll be able to glean from the ice core is still an open question. "This is *exploratory* science in the best sense of the word," said Eric Steig, a glaciologist at the University of Washington who was not involved in the study.

A Window into a Well-Preserved Past

Ice, like sedimentary rock, builds up over time. Each snowfall adds a layer, which gets compressed under new snow. Analyzing the chemical signals in those layers offers insight into past climate conditions. This data collection is urgent; glaciers, including those covering Mount Everest, are melting rapidly. It's important to collect samples before the evidence vanishes with the ice.

"This is *exploratory* science in the best sense of the word."

In preparation for the expedition, Potocki and Mayewski modified off-the-shelf equipment to make it as light as possible. They triple- and sometimes quadruple-checked their gear and brought a backup drill in case one failed. The last thing anyone wanted was an equipment malfunction.

Ultimately, Potocki collected a 10-meter-long ice core from 8,020 meters above sea level—more than a thousand meters higher than the previous record—on the South Col Glacier.

Mariusz Potocki (center with orange goggles) and the National Geographic and Rolex Perpetual Planet Everest Expedition team collect the highest ever recorded ice core sample at the South Col Glacier. Credit: Dirk Collins, National Geographic and Rolex Perpetual Planet Everest Expedition, www.NatGeo.com/Everest

Although the fieldwork went smoothly, the team encountered delays in processing the samples. "We've found the things we hoped to so far," Mayewski said of the early analyses. "The ice is well preserved in terms of a climate and environmental record," he continued, meaning that years, seasons, and possibly the frequency of storm events are distinguishable in the core.

To analyze the samples, the team is using a laser ablation system previously developed by Mayewski. A laser vaporizes a series of shards of ice about a quarter the width of a human hair. Those vapors are then transported with argon gas to an instrument that takes nearly 100 measurements from the sample.

Unlike other methods of ice core analysis that involve slicing sections of the core or melting it down, laser ablation is essentially nondestructive. Under a microscope, "it looks as if you're absolutely drilling a trench inside of this glacier," Mayewski said, but "when you take the ice out, you can't even see a scratch." Preserving the sample is important for repeatability and for maximizing the number of measurements that can be taken from each core.

The preciseness of laser ablation has another advantage. The researchers can look at the layers of ice in great detail. Instead of the 100 or so samples per meter that the sectioning and melting methods yield, laser ablation allows for 10,000–20,000.

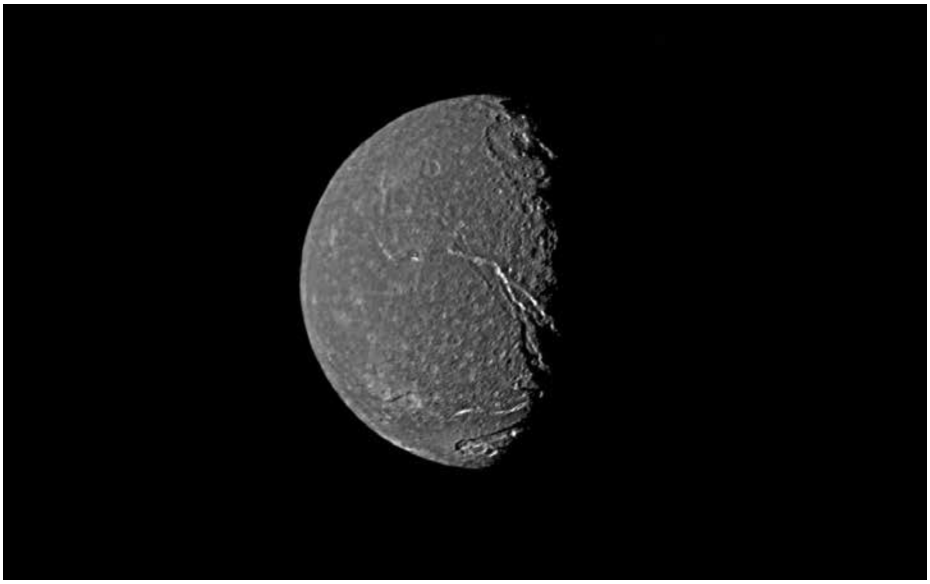
Not everyone agrees on the value of such high-resolution measurements, however. "There's probably no meaningful information at that scale," Steig said, although he is enthusiastic about the expedition. "I was merely pointing out that the resolution (micron-scale!) is so high that it goes beyond what's useful," he said on Twitter. Still, the researchers claim that with laser ablation they can not only identify seasonal variations but also get a sense of the severity of past monsoon seasons.

Regardless of the information the team is able to extract, collecting an ice core from the roof of the world is itself a remarkable feat. "I really felt so lucky I was able to collect such a good quality ice [core] at 8,000-meter elevation," Potocki said. "Mission accomplished."

And, yes, Guinness World Records did reach out.

By **Anna Blaustein** (@annablaustein), Science Writer

Do Uranus's Moons Have Subsurface Oceans?



"The moon methinks looks with a watery eye." —Titania, A Midsummer Night's Dream, *William Shakespeare. Above, Uranus's moon Titania as seen by Voyager 2 in 1986. Credit: NASA/JPL*

The solar system is rife with tiny, icy worlds. Many of them are moons of the gas giant planets and have been confirmed or are suspected to have liquid oceans beneath frozen ice shells. Jupiter's moon Europa and Saturn's moon Enceladus are two of the more famous examples of such worlds. Why wouldn't some of the moons of Uranus and Neptune, the solar system's ice giant planets, have subsurface oceans too?

Most planetary scientists agree that there's no reason why not, and a team of researchers found that a tried-and-true method of confirming the existence of subsurface oceans would work especially well for the moons of Uranus.

"The big question here is, Where are habitable environments in the solar system?" said Benjamin Weiss, a planetary scientist at the Massachusetts Institute of Technology in Cambridge. The discoveries of oceans on Europa and Enceladus "make a lot of us wonder whether there are many moons out there that although they're small, may still be warm." Weiss presented this research in December at AGU's Fall Meeting 2020 (bit.ly/moon-oceans).

Ocean Currents

During Voyager 2's flyby of the Uranus system in 1986, it sent back to Earth the first (and so far only) close-up views of the planet's five largest moons—Miranda, Ariel, Umbriel, Titania, and Oberon. Those images revealed that the moons are made up of a roughly 50:50 combination of rock and ices and, like most planetary satellites, have many craters. However, the moons' surfaces also display some of the classic signs of cryovolcanism, like fresh uncratered material and ridges, valleys, and folds.

"The big question here is, Where are habitable environments in the solar system?"

As with Europa and Enceladus, a subsurface ocean is one way those signs of recent geologic activity could have been created. Weiss and his team wanted to know whether a future spacecraft could discover such an ocean.

The researchers calculated the strength of the magnetic field Uranus would induce on a moon's hypothetical subsurface ocean and determined whether a future mission orbiting the planet would be able to detect that induced field. This is the same technique scientists with NASA's Galileo mission used in 1998 to confirm the presence of a subsurface ocean on Jupiter's moons Europa and Callisto.

An induced magnetic field works like this: As a moon orbits a planet, it also travels through the planet's magnetic field, which isn't the same strength or direction everywhere. The moon "feels" a changing magnetic field, a process that generates an electrical current. "If there's liquid water there and it's a little bit salty like ocean water on the Earth, then it can be conducting, meaning currents can flow in it," Weiss said. That flowing current will, in turn, generate its own magnetic field—an induced magnetic field. An induced field looks very different from a planet's magnetic field and so can be detected by a nearby magnetometer.

Using theoretical models of Uranus's magnetic field, Weiss's team calculated the strengths of the fields induced on Miranda, Ariel, Umbriel, Titania, and Oberon and found that Miranda's induced magnetic field was the strongest, at 300 nanoteslas, and Oberon's was the weakest, at just 3 nanoteslas. For comparison, the Galileo mission measured an induced magnetic field of about 220 nanoteslas at Europa and about 40 nanoteslas at Callisto. A subsurface ocean on Miranda, Ariel, Umbriel, and Titania would be well within the measurement capabilities of current spacecraft technology, Weiss said, although Oberon's field might be right on the edge of detectability.

Strength in Strangeness

Uranus's magnetic field, like so much about the planet itself, is quite odd compared with those of other solar system planets: The field is tilted by 59° from the planet's spin axis, and its center is shifted from the planet's center by about a third of the planet's radius.

Magnetic induction confirmed the presence of Europa's and Callisto's subsurface oceans, but Jupiter's very symmetric magnetic field made it impossible for the Galileo mission to figure out the oceans' depth, thickness, or salinity with its small number of flybys. The same is true of Saturn's magnetic field and Enceladus's subsurface ocean. But measurements of those properties might be possible for moons of Uranus.

"The key is that Uranus' field is non-spin symmetric, unlike Saturn's, and it rotates. We know these things, so [the technique] should work," said David Stevenson, a planetary scientist at the California Institute of Technology in Pasadena and a member of the Galileo team. Stevenson was not involved with this research. "The caveat is magnetospheric effects [of Uranus], which are not yet well characterized but are unlikely to kill the idea."

Detecting a signal would be "actually easier and more reliable" than other methods that might find an ocean.

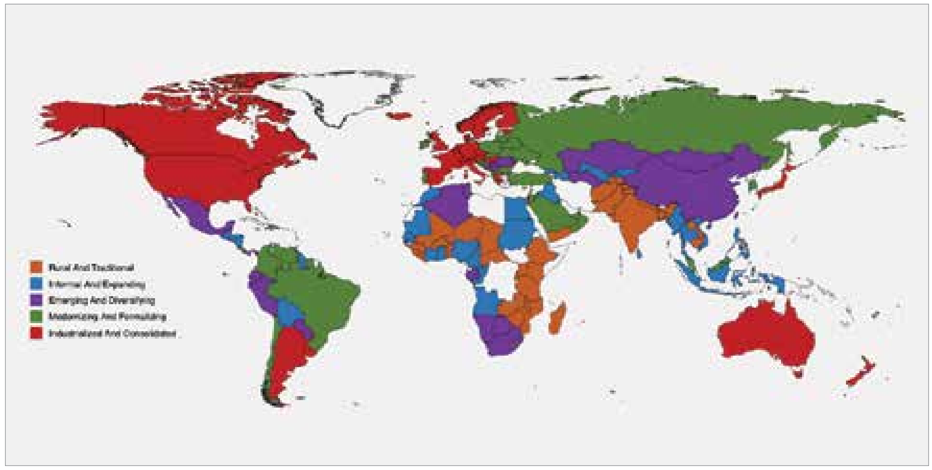
However, Stevenson cautioned, subsurface oceans in the Uranus system are likely to be farther beneath the surface than those in the Jupiter system simply because Uranus's moons are colder and so the icy shell is likely thicker. Although that might make the measured field weaker than estimated, he said, detecting a signal would be "actually easier and more reliable" than other methods that might find an ocean.

Uranus and Neptune are higher-priority targets for a spacecraft mission than they have been in the past because an opportune launch window opens up in the late 2020s. NASA, for example, is considering a Neptune mission called Trident, although no mission to Uranus is currently under consideration. However, "getting close enough to one or more of the satellites to see this—you have to get close, meaning within a satellite radius, roughly—is unlikely to be a feature of an early...mission to Uranus," which likely wouldn't arrive before 2042, Stevenson said.

A mission to an ice giant might be far off, Weiss admitted, but he hopes that this research "stimulates people to look even more seriously at the idea of sending a magnetometer investigation to Uranus or Neptune."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Food Systems Are Complicated. Food Data Don't Have to Be



A map from the Food Systems Dashboard shows different types of food systems around the world. Credit: Food Systems Dashboard, GAIN and Johns Hopkins University, 2020, Geneva, Switzerland, https://doi.org/10.36072/db

At a time when half of the fresh fruit purchased in the United States comes from other countries and sandwiches have carbon footprints, today's food landscape is giving some consumers more options.

Food systems, the webs of agricultural and commercial activities that bring food from farms to our tables, have never been so complex. This complexity impedes the work of researchers, planners, and others looking to make positive impacts on human health and the environment. A new tool developed by researchers at Johns Hopkins University and the Global Alliance for Improved Nutrition (GAIN) aims to help such decisionmakers by allowing them to distill loads of data on food systems into a Google Maps–like dashboard.

A Global Problem

Worldwide, nearly 1 in 10 people don't have enough food to eat, and 3 billion can't afford a healthful diet, according to a 2020 United Nations report (bit.ly/food-security-assessment). "The numbers are kind of scary," said Lawrence Haddad, executive director of GAIN.

Although the number of people struggling with hunger decreased between 1990 and the mid-2010s, the numbers have gone back up in recent years because of conflicts and political fragility in many parts of the world, said Haddad. Effects of climate change, such as increases in extreme weather and land degradation, aren't helping either.

At the same time, policymakers and businesses often emphasize profit over nutritionally or environmentally beneficial outcomes, said Haddad. "The system is not set up to [benefit nutrition or the environment]. It's set up to make money."

So he and his colleagues set out to create a tool for investigating agricultural, production, and distribution supply chains, as well as drivers of food systems like urbanization and gender equality, health outcomes like diet and nutrition, and other related factors. The result is a colorful online dashboard—the first to distill country-level data into one place—that lets users tinker with and explore more than 170 facets of food systems around the world (bit.ly/food-system-dashboard).

"You can't fix something that you can't measure," Haddad said. Now decisionmakers can zero in on failing parts of systems and tweak them to improve nutrition for consumers, increase crop biodiversity, or minimize greenhouse gas emissions.

How It Works

The goal of the dashboard is to make it easier for policymakers, businesspeople, and others to describe, diagnose, and enact changes in food systems.

"The fact that all the information we needed was available in one place was very valuable for us."

The dashboard includes information by country and year for a wide variety of indicators: Users can toggle among the average daily fruit consumption by adolescents, supermarkets per capita, and greenhouse gas emissions from fertilizers, for example. The data are presented on maps and graphs that change dynamically.

Haddad said that without the Food Systems Dashboard, it would take many months to find all the data and then clean, organize, and document them and put them together in a food systems framework.

It's a "one-stop-shop" database, said Destan Aytekin, a specialist with the food production nonprofit HarvestPlus who was not involved in creating the dashboard. With colleagues, Aytekin is using the dashboard to research nutrient-enriched staple crops in the Sahel region of Africa.

"The fact that all the information we needed was available in one place was very valuable for us, especially because we were looking to learn more about many countries in the region and gather data on many indicators at once," Aytekin said.

The dashboard pulls data from 30 different sources, many of them public. To facilitate some of the data aggregation, the dashboard team entered into a 10-year agreement with the market research company Euromonitor International, which collects data from food retail outlets. Euromonitor usually sells its data, said Haddad, but now the data are publicly available through the dashboard.

The Dashboard in Action: Hunger and El Niño

Ramya Ambikapathi is no stranger to food systems. As a postdoctoral researcher at Purdue University's Department of Public Health, she has worked in five countries studying issues ranging from breastfeeding practices to the role of fathers in family nutrition outcomes. Recently, she mapped effects of COVID-19 on food systems.

In June, Ambikapathi perused the database for insights that would inform a research question that had been on her mind for years. She wrote her doctoral thesis on the El Niño–Southern Oscillation (ENSO) and how it influences children's nutrition in the Peruvian Amazon. The climate oscillation has intimate effects on food systems because it changes weather patterns around the world.

Ambikapathi wanted to know how communities survived these shifts, like extreme changes in precipitation.

She first selected countries most affected by ENSO, a group that spans the globe from Indonesia to Somalia to Mexico. She then ranked the countries in the dashboard to get a feeling for how access to food changes throughout the year, which can be affected by factors like supermarket availability or people's ability to weather hard times using personal remittances.

Her initial analysis of 15 countries found that Haiti, Kenya, Zambia, and Zimbabwe are most vulnerable to ENSO. "Zambia, in particular, with the lowest per capita remittances, may have a longer rate of recovery from ENSO exposures when compared to other countries," Ambikapathi said. She added that her estimates and hypotheses are preliminary and would require deeper study to test.

Ambikapathi's assessment won first prize in the dashboard's 2020 competition. She has proposed creating a review of food systems around the world affected by chronic climate shocks using the dashboard.

"Zambia, in particular, may have a longer rate of recovery from ENSO exposures when compared to other countries."

What's Next?

Perhaps the Food and Agriculture Organization of the United Nations will adopt the dashboard in the future, said Haddad, but funds to maintain and further develop the dashboard must be in place first. Current funding comes from a grab bag of international foundations, agencies, research centers, ministries, and development programs. The dashboard will require about $10 million to maintain over the next 5 years, and Haddad and colleagues have raised $1 million so far.

Haddad, a self-described data geek, said the dashboard will continue to evolve. It may someday feature state- and province-level data too. And work is underway with partners in India, Indonesia, and Nigeria to help those countries develop their own dashboards to complement the existing dashboard's global view.

"When you really get into the weeds, you find you want more and more data," Haddad said. "[The dashboard is] really helping people see the whole picture."

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Will Rising Temperatures Make Rice Too Toxic?

A rice paddy in Cambodia. Credit: University of Washington

Rice feeds about half the world, but it is vulnerable to rising temperatures. Increased heat boosts the arsenic uptake from soil to rice plants, perhaps to levels toxic to infants. A new analysis presented at AGU's Fall Meeting 2020 revealed the root cause of this potentially poisonous transfer, providing another clue for field scientists working to address the problem (bit.ly/arsenic-rice).

"We found strong evidence that what's really controlling this process is a microbially mediated reaction that takes arsenic out of the soil and [puts it] into the water," said Yasmine Farhat, a doctoral candidate in environmental engineering at the University of Washington and lead author of the study, which appeared in *Science of the Total Environment* in October (bit.ly/arsenic-exposure).

"Real-world solutions to curtail high arsenic levels in rice should focus on restricting availability of the toxin."

Getting to the Root of the Problem

Rice is particularly vulnerable to arsenic uptake because unlike most crops, it grows in flooded conditions with anoxic soil. Microbes that thrive in these anoxic environments release arsenic into the soil's pore water through normal metabolic reactions. Once liberated from soil particles, this pore water arsenic can be taken up by the rice plant's roots.

Previous studies have focused mainly on heat stress and its impact on how rice plants grow, possibly making them more likely to concentrate arsenic. What the new research indicates, however, is that "bioavailability may be more important," Farhat said.

Farhat's team grew rice plants in four greenhouses set to daytime temperatures of 25.4°C, 27.9°C, 30.5°C, and 32.9°C. (Nighttime temperatures were about 2°C cooler.) Each chamber contained pots with soil from a rice field in Davis, Calif., with relatively low levels of arsenic. The team then sampled plant tissue, soil, and pore water as the plants grew.

Results showed a strong link between rice grain arsenic concentrations and temperature and confirmed that in hotter conditions, soil pore water contained more arsenic. Farhat's team used a mass balance calculation to show that this increased bioavailability of arsenic was the main driver of higher arsenic levels in the plants.

That her team used soil low in arsenic is crucial, Farhat said: "Elevated growing temperatures may increase the risk of dietary arsenic exposure in rice systems that were previously considered low risk."

Potential Solutions

The authors suggested that real-world solutions to curtail high arsenic levels in rice should focus on restricting availability of the toxin. One approach is to let soils dry out intermittently, a method known as wetting and drying.

"If you give the soils time to breathe, or become oxygenated, it is known to reduce arsenic quite a bit," said Manoj Menon, a soil and environmental scientist at the University of Sheffield in the United Kingdom who was not involved in the study. Another potential solution, Menon said, is planting arsenic-resistant varieties of rice.

In locations where arsenic availability mitigation is not feasible, cooking treatments could help. In a recent paper on which he was the lead author, Menon demonstrated a cooking method called "parboiling and adsorption," which removed 54% of inorganic arsenic from brown rice and 73% from white rice (bit.ly/arsenic-removal).

Taking Action

In many areas across the globe, especially the tropics, people consume rice multiple times a day. For some, alternative food staples are simply not available. A rising concentration of arsenic in rice poses a slowly growing but dire threat to these communities.

"It's a big problem in South and Southeast Asia—anywhere where they irrigate with groundwater," said Farhat, who has done extensive fieldwork in Cambodia.

According to Menon, no single solution will solve the problem of arsenic in rice. "Although this is common across Asia, there are regional differences," he noted. The most critical step now, he said, is for researchers to bridge the gap between their work in the lab and agricultural practices in the field: "We have to educate people, at the community level."

By **Nikk Ogasa** (@nikkogasa), Science Writer

Opposite: Mae Mu/Unsplash

Contamination of Medicinal Plants Has Implications for Indigenous Health

Amid the politicization of environmental policy in the United States, there has been increasing discussion of the hazardous effects of mining on human health. The historical legacy of uranium mining in the West, for instance, has left Indigenous communities susceptible to health conditions, including lung cancer.

Few studies, however, have evaluated the potential health effects of mining on medicinal plants, which are crucial aspects of Indigenous culture. In a new project, a team from the University of Arizona led by Richelle Thomas is seeking to identify the effects of arsenic and uranium on the traditional medicinal plants *Salvia* (an inhalant) and *Thelesperma* (a tea additive) and the ensuing effects on human organs. The team was recently awarded the MIT Solve Indigenous Communities Fellowship and is starting greenhouse studies this year. Thomas presented an outline of the project at AGU's Fall Meeting 2020 (bit.ly/medicinal-plant).

Richelle Thomas is leading a new study investigating the legacy of uranium mining on traditional medicinal plants. Credit: Richelle Thomas

There are more than 500 abandoned uranium mines across the Navajo Nation.

Using analytical chemistry and biological techniques, the team will quantify metalloid concentrations in plant and soil samples. Researcher Gilberto Curlango-Rivera studies these concentrations in the root systems of plants. "Root systems have specialized cells that interact with microorganisms in the soil and also with abiotic factors such as metals," he said. "My interest is to see how roots and these metals interact to offer possible solutions to contamination."

Karletta Chief, a Diné hydrologist and an associate professor at the University of Arizona, noted that there is not a lot of scientific investigation related to the chemistry of metalloid uptake in medicinal plants, despite the fact that those plants are sacred and very important to Indigenous communities. "Combining that with the fact that there are over 500 abandoned uranium mines across the Navajo Nation, [identifying an] additional exposure pathway which has not been fully and deeply investigated...that's very unique and important," Chief said.

Thomas worked with sage, a plant widely used for ceremonial purposes, as part of her master's thesis. For her Ph.D., she wanted to expand her focus to medicinal plants that are widely available. "Navajo tea is even commercially available now," Thomas said. By studying medicinal plants that are also commercially available, Thomas hopes her research will have a far-reaching impact that will raise awareness inside and outside Indigenous communities.

Scientific and Traditional Perspectives

Thomas's research interest stems from her family background. "My maternal grandfather was a traditional Navajo practitioner," Thomas said. "Before his passing, he was asking about the influence of heavy metals on the environment as well as people."

Thomas views her work as following in her grandfather's footsteps, combining a Westernized laboratory-based approach with Indigenous perspectives. Her sister Meredith Lynn Thomas, cultural advocate and research assistant on the project, said that their grandfather emphasized combining scientific and traditional perspectives and using them proactively. Richelle strives to translate her findings "not just to the scientific community, but also to the people who are directly impacted—medicine men and women, communities, and anybody who purchases it in the public." She emphasized the need to communicate risks in an accessible way, rather than giving people a number that they as nonscientists may not understand. "She had the community involved from the get-go," Meredith said. "She took that first step as a responsible researcher to get their consent."

Many current researchers are non-Native and don't share their findings, resulting in some Indigenous communities being hesitant to participate. Thomas's study is "unique because you have a Native American female who's very rooted in her community, her culture, her tradition and language doing cutting-edge research and using scientific tools to address a very culturally based research question," said Chief. "Richelle is very grounded in the ethics of doing this type of research, especially considering that it's a sacred medicine and that it has to be protected."

Thomas plans on involving traditional practitioners closely in her findings. "Working with the Navajo, like any minority population, requires a different approach," she said, and cultural sensitivity is critical. "I'm

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taking a very big piece of the belief system [medicinal plants] and saying it's potentially dangerous."

Team member Robert Root emphasized the importance of developing the trust of various stakeholders and serving as a liaison. "Wherever it leads, they'll be empowered to make decisions based on her translation of the research," Root said.

Grassroots Change

Thomas hopes for positive change in federal Indigenous policy with the new Biden administration but emphasizes the importance of implementing change from the ground up: "It really needs to start from a grassroots level with traditional practitioners, then become adopted at the tribal level, and then hopefully it turns into something bigger."

"Not every tribal member out there is the same...so it's really important to engage with all the different tribal members within a community."

Chief echoed this sentiment: "[Every step of the research process] has to involve community members, tribal leaders, educators, and grassroots activists so it can be a multidimensional, deep engagement," she said. "Not every tribal member out there is the same...so it's really important to engage with all the different tribal members within a community."

The team will develop environmental justice guidelines that can be transferable to other Indigenous Peoples and used to craft policy. Ongoing environmental injustice faced by diverse Indigenous communities demands awareness, the team emphasized. "Many people are not even aware that [we] exist," Thomas said. The scientists "are not aware of how we can help them. A lot of that comes from self-reflection. History has never really been written in the books, and even the issues we have today are not really well known."

By **Ria Mazumdar** (@riamaz), Science Writer

Modeling Groundwater and Crop Production in the U.S. High Plains

Many agricultural fields in the U.S. High Plains, such as this field in Nebraska, are irrigated using groundwater from the Ogallala Aquifer. Credit: iStock.com/RiverNorthPhotography

An international team of more than 2 dozen researchers has found a novel approach to modeling groundwater levels and crop production to forecast future resource availability and yields. The model the researchers developed was inspired by ecology's Lotka-Volterra equations, a mathematical explanation for the cyclical population dynamics of predator and prey species.

Previous models for forecasting groundwater levels have relied on Hubbert's curve, an equation with its basis in production rates and demand for a given resource. (The model is named after M. King Hubbert, the geologist who famously predicted in 1956 that crude oil production would reach a peak in the 1970s.) However, the research team behind the new model wanted to develop a method that would couple the dynamics of groundwater withdrawals and crop production. As Assaad Mrad, the lead author on the study and a Ph.D. candidate at Duke University, explained, "we looked at crop production as the predator and groundwater resources as the prey, and we found that [this model] describes the trends in groundwater extraction and crop production rates very accurately. These were the seeds of the project that stemmed from the goal of introducing more rigorous mathematical techniques to [the science of] sustainability."

"That kind of modeling approach that is drawn from ecology had not really been applied to this kind of physical system before," said Erin Haacker, an assistant professor of hydrogeology at the University of Nebraska-Lincoln who was not part of the new study. Haacker noted that compared with other hydrologic modeling, which tends to use "a much more physical-based approach" that sets expectations based on physics and checks to see whether they match the data, the model developed by Mrad and his colleagues "uses a really empirical statistical approach" that "fit the [model's] parameters

"We looked at crop production as the predator and groundwater resources as the prey, and we found that [this model] describes the trends in groundwater extraction and crop production rates very accurately."

based on what the observation data told them."

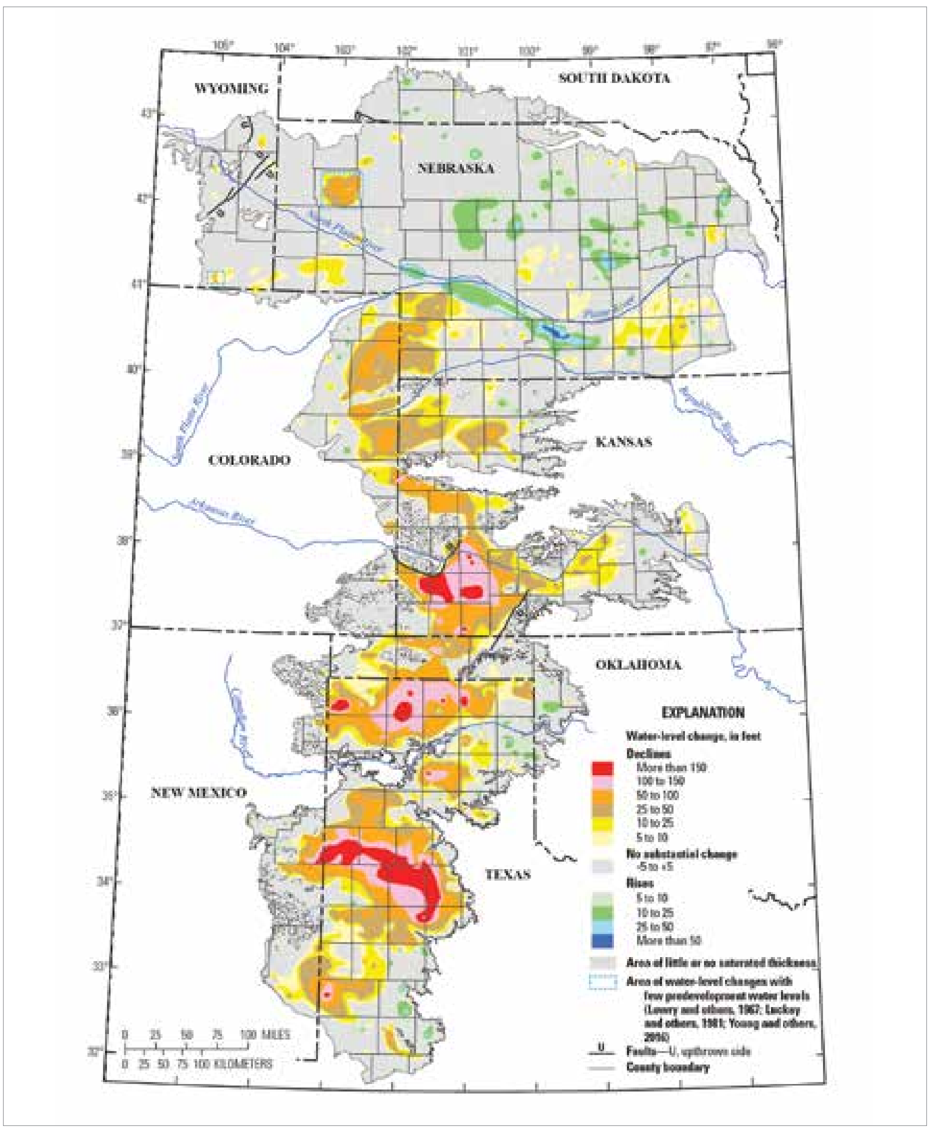
The paper detailing the innovative methodology was published in the *Proceedings of the National Academy of Sciences of the United States of America* in October (bit.ly/groundwater-depletion).

Putting Their Ideas to the Test

To test their ideas, Mrad and the other researchers gathered irrigation and crop yield data for Nebraska, Kansas, and Texas. Portions of all three states depend on the Ogallala Aquifer, a vast underground reservoir whose declining stores have been causing concern for years.

Also called the High Plains Aquifer, the Ogallala supplies water for almost 30% of irrigated crops and livestock in the entire country. The aquifer's north–south orientation extends through different climates, ranging from hot and dry in the Texas Panhandle to comparatively wet and cool in Nebraska. The crosscutting aquifer allowed researchers to "disentangle the effect of climate on groundwater recharge, crop production, and groundwater extraction," Mrad said.

The model found that in Texas, crop production initially peaked 9 years after a peak in groundwater withdrawal. After the state began using more efficient irrigation technology, the state's groundwater extraction and crop production both reached a second peak with an increased lag of 15 years between them. In Nebraska, where higher precipitation replenishes the aquifer at a higher rate, the researchers' model forecast that crop production might continue to increase beyond the year 2050. In Kansas, the model projected that the state's crop production would peak 24 years after its groundwater withdrawals peaked.



Water levels in the Ogallala Aquifer have declined significantly since industrial agriculture and development began in the mid-20th century. Credit: USGS

"What we found is that [a method based on Hubbert's curve] is applicable only for cases such as Texas," Mrad said, "where your groundwater use is very nonrenewable" because of a substantially lower recharge rate. For regions with a higher recharge rate, like Nebraska, Mrad said, "Our studies showed that if you use these methods [based on Hubbert's curve], you will not get the correct results."

New Data: Agricultural Technology

Mrad's model is sensitive to historical improvements in irrigation technology, but he acknowledged that "our projections assume no disruptive technological improvements in the next 30–40 years."

If such improvements are developed, it may not take long for farmers to start using them. Dana Porter, an agricultural engineer and irrigation specialist with Texas A&M University and Texas Extension, explained that farmers in the Texas Panhandle, where agriculture is a large part of the local economy, have many incentives to adopt better irrigation technologies when they become available. "We're a semiarid region, so our crop production in this area is water limited," she said. "There's an economic advantage to adopting the technology. The aquifer is deep, so it costs a lot to pump it up there, and we want to be as efficient as possible with the water, because a little bit of increase in efficiency can result in a noticeable improvement in yield, especially in a drought year." Porter was not involved with the new study.

The idea for the new paper originated in discussions at the Ettersburg Ecohydrology Workshop in Germany, a 2018 gathering of 29 experts and graduate students from 11 countries. Mrad was not part of this workshop, but Gabriel Katul, Mrad's adviser and the second author on the new paper, was one of the experts in attendance.

By **Jady Carmichael** (@jadycarmichael), Science Writer

Feedback Loops of Fire Activity and Climate Change in Canada

Smoke plumes from active wildfires ascend over northern Canada in 2015. Credit: Ellen Whitman, Natural Resources Canada

Wildfires burned more than 7,750 square kilometers of Alberta's forests last year. New research indicates that the conflagrations are part of a pattern showing increased average burned areas every year since 1970, and climate change is poised to accelerate this trend.

Ellen Whitman, a forest fire research scientist from Natural Resources Canada, used historical records as well as satellite data from the Landsat program to analyze how the frequency, size, and distribution of forest fires in the province of Alberta changed between 1970 and 2019—research she presented at AGU's Fall Meeting 2020 (bit.ly/Alberta-forest-fires). She and coworkers from the Canadian Forest Service and the U.S. Forest Service found that forest fire activity in Alberta increased according to a plethora of metrics over the past 49 years, with the number of fires that consume at least 200 hectares of land almost doubling and the average area burned per year increasing approximately fifteenfold.

"Every variable we were interested in seems to have demonstrated some type of change over time," Whitman said. Variables included data surrounding fires in wetlands and old-growth forests, and the recovery of forests after a fire.

Feedback Loops

Even wetlands, with their low propensity for fire, are burning more frequently. Whitman said that the proportion of burned wetland forests has increased approximately fivefold, from comprising only 3% of land burned by wildfires in 1970 to 15% in 2019.

Whitman documented a feedback loop between wetland fires and a warming climate. Increased fire activity correlated with increased temperature, as well as with decreased precipitation and relative humidity—all hallmarks of climate change. These changes add up to a drier environment, and associated periodic drops in the water table allow even wetlands, which are typically associated with fire control, to burn.

The feedback loop incorporating wetland fires, the warming climate, and burn area is especially relevant to peat fires. As climate change increases the prevalence of peat fires, the loss of peat bogs could further accelerate climate change. These oxygen-poor accumulations of waterlogged vegetation compress carbon rather than degrade it, making them important carbon sinks. When they burn, carbon is released into the atmosphere, and the bogs become carbon sources.

The Alberta study also showed that old-growth forests have suffered from increased fire activity, and their demise could further accelerate climate change. "We're seeing a shift toward more rapidly growing, disturbance-favored species like aspen and Jack pine to the detriment of more long-lived and more carbon-storing species like white spruce and black spruce," Whitman said.

Ernesto Alvarado is a forest ecologist at the University of Washington who said that Whitman's work confirms a lot of what fire researchers have long suspected. He's particularly concerned that increases in fire frequency and severity will reduce tree cover. In northern Canada, increased sunlight hitting the forest floor and wildfires could thaw permafrost, which locks carbon-storing soil under the forest floor.

"Carbon storage in those ecosystems took thousands of years to get to its current point," Alvarado said. "Now they can go up in smoke, or be released, in a matter of years."

> **"Carbon storage in those ecosystems took thousands of years to get to its current point. Now they can go up in smoke, or be released, in a matter of years."**

Difficult Decisions

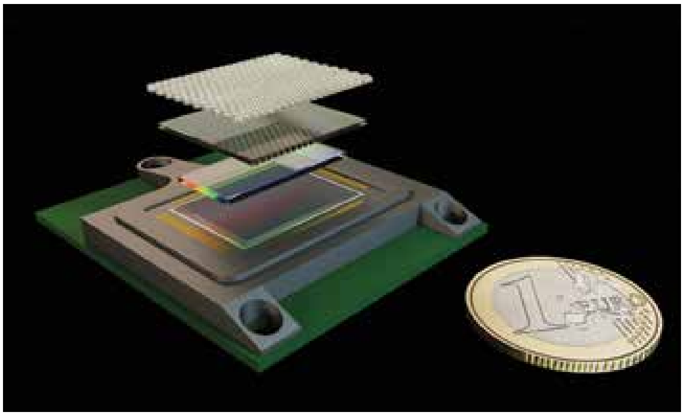
Historically, Canadians have assumed that forests will return to their original states after forest fires, Whitman said. But as fires intensify, forests are being pushed past their ability to adapt. In addition to accelerating climate change, long-term changes in tree cover could affect Canadians who rely on forests for resources like timber and fresh water. Increased fire activity also increases the vulnerability of communities in remote areas surrounded by forests.

Forestry managers may also find themselves faced with severe fires they're unable to suppress or an overwhelming number of simultaneous fires. Some agencies already are choosing which fires to fight on the basis of human safety, economics, and their ecological impact.

"We're going to have to make some innovative and, I think, difficult decisions about how to manage fire and keep people safe," Whitman said.

By **Saima Sidik** (@saimamaysidik), Science Writer

Exoplanet Earth: An Ultimate Selfie to Find Habitable Worlds



The LOUPE mission instrument (here with a 1-euro coin for scale) includes layers of liquid crystals that will continuously collect and analyze photons of light reflecting off the entire Earth disk. Credit: Jens Hoeijmakers

Twenty-five years after we discovered the first world orbiting another star, our exoplanet catalog numbers 4,301 and climbing. However, only about 51 exoplanets have been truly seen. This small collection of directly imaged worlds comprises a variety of stellar objects, from failed stars known as brown dwarfs to young Jupiter-like gas giants to the odd hellish lava world.

Each observed exoplanet was picked out from the glare of a nearby sun because of its extreme size, orbit, or temperature. Collecting light from more Earth-like planets remains beyond the reach of today's telescopes. The necessary technological refinement is only a matter of time, however, and the payoffs could be significant.

The Potential in Planetary Pixels

At Delft University of Technology in the Netherlands, researchers have been investigating what artificial intelligence (AI) algorithms could "see" within the light bouncing off more homelike exoplanets. Astrophysicist Dora Klindžić is particularly interested in light polarization—the orientations in which photons vibrate.

Polarimetry has long precedence in planetary science. In the 1970s, NASA's James Hansen used it to reveal that Venus's clouds were made of sulfuric acid. More recently, the Gemini Planet Imager in Chile conducted polarimetry surveys of the protoplanetary disks surrounding newly formed stars to directly image and measure the composition of any young gas giants.

Klindžić believes that the fingerprints of more terrestrial surface features are also being broadcast in the vibrating photons that rockier exoplanets reflect out into space. "If we have a planet which has clouds, liquid water, continents, snow, and ice, each one of these types of reflecting surfaces is going to be discernible in the polarization of light," she said.

Last year another team at Delft proposed a distinct color signature for polarized light bouncing off an imagined ocean exoplanet. However, Klindžić reasoned, if scientists are looking for signs of life, algorithms to analyze these planetary pixels need training on our only known living planet. This analysis means taking polarimetry off Earth to provide a whole-planet perspective. Klindžić is targeting the Moon as the ideal vantage point. Her new paper, published in *Philosophical Transactions of the Royal Society* in collaboration with colleagues at Leiden Observatory and the company cosine remote sensing, presents the LOUPE mission—the Lunar Observatory for Unresolved Polarimetry of the Earth (bit.ly/observing-exoplanets).

The mission will take what Klindžić describes as "the ultimate Earth selfie." Likely to resemble an unresolved pale blue dot, the selfie will contain all the polarimetric information coming off Earth's illuminated disk—a continuous stream of photons whose vibrations are shaped by their reflection off that familiar patchwork of weather systems, oceans, continents, and ice sheets, all rotating in and out of view. If an AI tool can learn to extract such surface and atmospheric features, scientists could characterize similar signatures from exoplanet light.

For a mission with such lofty aims, LOUPE is a modest instrument. A coin-sized spectropolarimeter weighing a few hundred grams, its key components are liquid crystals, like those in a laptop screen. These crystals will count Earth-reflected photons while characterizing their wavelength and polarization. Because of Earth's brightness in the Moon's sky, a stationary wide-field lens will avoid the need for any mechanical point and focus system. This lens will keep weight and power requirements low, allowing LOUPE to piggyback on a future rover or lander or even on the planned lunar Gateway space station.

Looking at Earth in a New Light

Klindžić is not alone in looking to Earth to better understand worlds far beyond. At NASA's Jet Propulsion Laboratory, Jonathan Jiang is training his own AI on simulated exo-Earth pixels based on the photon flux data collected by the DSCOVR satellite. At the University of Colorado Boulder, Allison Youngblood used the Hubble Space Telescope to explore the earthshine reflected off the Moon during a blood moon eclipse. She detected ultraviolet signals of atmospheric ozone, a potential biosignature.

"Polarimetry provides many more details than traditional imaging or spectroscopy. So even though direct imaging of Earth-sized planets is several decades away, it really is the future for exoplanet characterization. I think it's important to do experiments like LOUPE now, when the telescopes that will directly image exoplanets are still being designed," said Youngblood.

The Delft team is building LOUPE prototypes with a 2022 launch window in mind and an eye on proposed coronagraphic telescopes, such as the Nancy Grace Roman Space Telescope, which will mechanically block starlight to reveal orbiting exoplanets. Klindžić also points to polarimetry instruments planned for NASA's Habitable Exoplanet Observatory and Large UV/Optical/IR Surveyor mission concepts and believes LOUPE's benchmark signal for an archetypal Earth could help these missions bring some distant, but perhaps familiar, worlds into focus.

"We are looking at ourselves to know others," Klindžić said.

By **James Romero** (@mrjamesromero), Science Writer

Building an Early-Career Researcher Community from the Ground Up

Doune Hill towers over a peat bog in Scotland. Credit: Michal Klajban/ Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

As researchers begin their careers, it is helpful for them to have a network of peers with whom they can collaborate and develop the direction of their future research. Unfortunately, the COVID-19 pandemic has limited networking opportunities for such scientists. In response to these limitations, an international group of early-career scientists working within the peatlands research community has developed its own network—the Peatland Early Career Researcher Action Team (PEAT)—to virtually forge connections and share insights.

Peatlands are found around the world, from the tropics to the Arctic. "The peat community is small…but the work we do is huge on a global scale in terms of [studying] the carbon cycle," said Scott Davidson, one of the coleaders of PEAT and a postdoctoral fellow at the University of Waterloo in Canada.

PEAT developed after Clarice Perryman, one of its coleaders and a Ph.D. student at the University of New Hampshire, reached out to her early-career colleagues in Canada, Sweden, and the United States to convene an eLightning session at AGU's Fall Meeting 2020 (bit.ly/PEAT-network). Despite being from different subdisciplines, continents, and time zones, the group found it fairly easy to connect with each other virtually. They decided to expand these connections into a larger early-career researcher (ECR) community. "We felt like it was something that the peat community wanted," said Sophie Wilkinson, one of the coleaders of PEAT and a postdoctoral fellow at McMaster University in Hamilton, Canada. She followed up by sharing that more than 40 people from six countries attended PEAT's last Zoom-based social.

PEAT's focus is to develop a network that combines community building with professional development and opportunities to be involved in the larger scientific community. The organization's first initiative, outside of video-based social events, was connecting the largely untapped pool of early-career reviewers with journal editors through a reviewer directory. "Everyone needs papers reviewed," Wilkinson said, "and yet there are still ECRs that are not on these lists who want the chance to review something."

PEAT leaders stressed that following the global pandemic, they will continue holding virtual social events to make sure that their new connections are sustained. They also hope to develop a seminar series to encourage early-career researchers to present their work to their community's global audience.

Interdisciplinary Endeavor

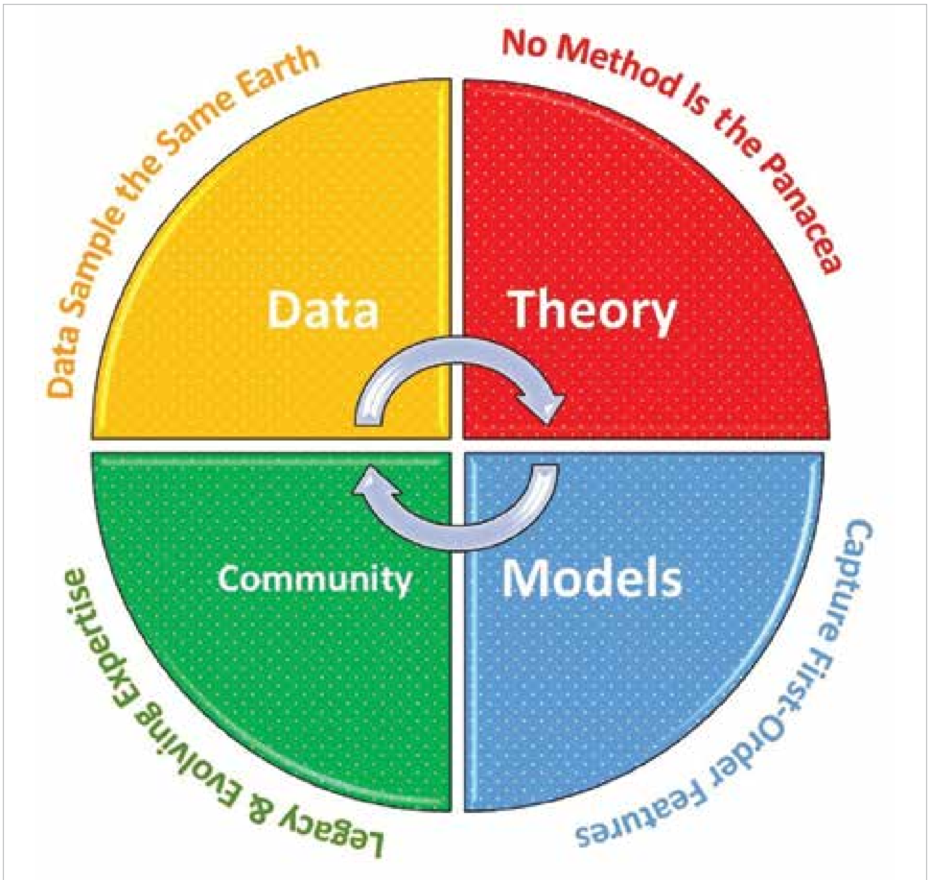
PEAT is open to undergraduates through early-career faculty in relevant fields such as biogeoscience and hydrology. Recognizing that issues of importance to peatlands are cross-disciplinary in nature, the group also invites social scientists in fields including paleoarchaeology, history, and economics. Ultimately, PEAT leaders said, the group wants the future of peatlands research to happen in an open, interdisciplinary, and highly connected way. "The balance between [being] productive in some way but also friendly and accessible to people is kind of key for us," Davidson said.

When asked about the importance of ECR-initiated communities to the future of science, Sarah Shakil said, "It is beneficial to have these organizations. I think this really helps facilitate relationship-building early on." Shakil is a Ph.D. candidate at the University of Alberta and was involved with the Association of Polar Early Career Scientists Council from 2018 to 2020.

"One of the great things about the PEAT ECR team from an outsider's point of view is that people are already working on projects," Shakil added. The PEAT community is a multidisciplinary "way to bridge people's work so you can get a whole system understanding of what is going on."

By **Hadley McIntosh Marcek** (@waterwings88), Science Writer

Shedding Light on the Mantle with a 3D Model



This chart outlines the four prongs (data, theory, model, and community) and underlying tenets of the 3D reference Earth model (REM-3D) project. Credit: P. Moulik, rem3d.org

Earth's mantle—the 2,900-kilometer-thick layer of rock beneath the crust—remains enigmatic, even to the scientists who study it.

"When it comes to the deep Earth, which is one of the unexplored frontiers of our planet, we simply can't drill deep enough to make any measurements of temperature or composition," said Pritwiraj Moulik, a postdoctoral associate in the University of Maryland's Department of Geology.

That's why Moulik and other geologists are using seismological and other geophysical measurements to make a three-dimensional reference Earth model (REM-3D) of the mantle that can be used for everything from better understanding earthquakes to neutrino geosciences. The team presented project updates at AGU's Fall Meeting (bit.ly/REM-3D).

Scientists rely on measurements of seismic waves, which are produced by earthquakes or explosions, to map out the interior of Earth, similar to how doctors use computerized tomography to understand what's going on inside a patient. Because the velocity of a seismic wave varies depending on the temperature and makeup of what it's traveling through, researchers can use those measurements to create 3D images of mantle features.

This process, called seismic tomography, is not new. But what makes the REM-3D project unique is that the team collected data and feedback from geologists and other scientists around the world. The number of data points is staggering: Researchers received 227 million surface wave measurements. And they incorporated four different kinds of waves, each of which better reflects a different part of the mantle, to finely tune the model.

"Incorporating all of these diverse constraints and the broad expertise in the community is a challenge because there are substantial differences in techniques," said Moulik, who stressed that it was "remarkable" how much data—and time—other deep-Earth researchers contributed to the project.

Max Rudolph, an assistant professor in the University of California, Davis's Department of Earth and Planetary Sciences, agreed that community involvement from deep-Earth researchers around the world makes this project stand out. "And I think the fact that this has taken so long to come to maturity really reflects the monumental nature of the undertaking," he said.

New Discoveries and Future Projects

In crunching the data, the team has already made new discoveries about the mantle. For example, there has been some debate among geologists about the structure of rare, thousands-of-kilometers-wide mantle upwellings. Members of the team were able to show that the lower parts of the upwellings have a different, denser composition than the upper parts, which allows them to last for hundreds of millions of years instead of being transient features, said Moulik.

Rudolph, who studies geological fluid mechanics, plans to use the 3D mantle representation in his own research to model mantle flows. He also envisions the new project serving as a launching point for smaller-scale models that could show finer levels of detail. Moulik echoed that idea, saying, "We want to be able to describe the haystack first with the 3D reference model before we go about finding needles."

The new model could also help seismologists more accurately measure the magnitude and other properties of earthquakes, which they currently often do by fitting individual seismogram measurements with older, one-dimensional reference models. And Moulik noted that techniques developed to make this model could eventually be used for similar efforts to probe the interiors of other rocky planets.

The model, as well as Web-based apps and underlying data sets, will ultimately be available to the public.

By **Elizabeth Gribkoff** (@eliz_gribkoff), Science Writer

Enhancing Food Security Through Earth Science Data

Produce for sale in an open-air market in Accra, Ghana, in the summer of 2019. Credit: Molly Brown

Food security is defined as all people, at all times, having physical, social, and economic access to sufficient, safe, and nutritious food for an active and healthy life. Food insecurity exists when any of these factors is impeded. Chronic food insecurity is usually the result of persistent poverty. Acute food insecurity, on the other hand, is related to human-induced or natural shocks to the food system—such as a drought or flood—that reduce short-term food availability or access, particularly for those already experiencing chronic food insecurity.

Earth science observations have been used for decades to evaluate food production in countries facing food insecurity, but they've been used only sporadically. Weather and climate variations have profound effects on crop production and, ultimately, food security, although such observations are still not being used regularly to understand agriculture and inform food security decisionmaking. The challenge for scientists, modelers, and policymakers is connecting real-time geospatial Earth science data to those who operate the food system, who are largely rural and lack the technological expertise to respond.

Over multiyear timescales, climate extremes and global environmental change influence food production and the well-being of agricultural communities in complex ways that are challenging to assess to any degree of certainty [*Vermeulen et al.*, 2012]. Meanwhile, weather during the growing season affects how well crops grow in a given year and thus the income of farmers, traders, wage laborers, and others in the agriculture sector, which in turn affects entire economies on local, regional, and potentially national and global scales. Acute food insecurity from repeated weather shocks can eventually lead to chronic malnutrition, which has significant economic and physical consequences for affected communities [*Brown et al.*, 2020].

The challenge for scientists, modelers, and policymakers is connecting real-time geospatial Earth science data to those who operate the food system, who are largely rural and lack the technological expertise to respond.

Earth science data and observations can quantify weather and climate impacts on a region and can be integrated into predictive models to inform adaptation plans. But evolving rural economies to allow for the application of such data requires adoption of new agricultural technologies and investment in rural livelihoods that can strengthen the broader food system.

Creating Comprehensive Data Sets for Farmers

Regions with rural livelihoods are dominated by small-scale agriculture, such as those in sub-Saharan Africa, where most owners of the approximately 33 million small farms are also often food insecure and live below the official poverty line [*Gassner et al.*, 2019]. Although rural economies vary, most smallholder farmers today have stagnant incomes and falling yields, even in places where rural populations are growing. Effects of climate change are further stressing these areas.

If these farmers are to increase production, they will need reliable information about local market prices for their crops as well as the cost and availability of agriculture inputs (e.g., seeds, fertilizer, machinery, and labor) and an understanding of the best management practices to reduce the impact of pests and weather variability on production. However, there are very few data sets from which to generate this information for smallholder agriculture, particularly for subsistence farms, which tend to be isolated from global market forces. Data on subsistence agriculture that are sufficiently localized and up to date are very difficult to obtain because of the diversity of crops, cultivation practices, and ecologies of agricultural regions across the world.

Some organizations are beginning to address this challenge. The World Bank's Living Standards Measurement Study-Integrated Surveys on Agriculture is a data collection project at the household level in eight countries in sub-Saharan Africa. One major goal of the project is to foster innovation in sustainability methods specifically for small farmers. But this and other efforts, like the follow-on 50×2030 Initiative, are still quite limited in scope and do not integrate much near-real-time Earth science data.

Using Earth Science Data to Improve Food Security

A variety of institutions concerned with food security in low- and middle-income countries are engaging with the Earth science community. Given the enormous variety of small farms around the world—from shifting cultivation in Colombia's rain forest to dryland millet farmers in northern Niger to paddy rice farmers in Cambodia—constantly collecting on-the-ground information about these communities is unrealistic. However, satellite observations already being collected by geoscientists can help relieve data collection burdens.

For example, in Uganda, anomalous vegetation data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite are the primary trigger for the government's Disaster Risk Financing (DRF) fund. In 2017, satellite data were showing that a drought was going to affect crop yields. The early warning allowed the government to use the DRF fund to provide relief to around 150,000 Ugandans who would have been affected by the food shortage. Initiatives like this one, which work to integrate Earth science information to improve food security decisionmaking, could be transformative.

There are very few data sets from which to generate this information for smallholder agriculture, particularly for subsistence farms, which tend to be isolated from global market forces.

In 2011, the G20 launched a plan to foster international coordination and transparency regarding food production. The platform for this effort is the Agriculture Market Information System, or AMIS, which assesses global food supplies with the aim of preventing or preparing for market shocks and uncertainty. AMIS relies on agricultural experts who provide regional market and policy information. It also relies, crucially, on geoscience data. Those data are provided by GEOGLAM (Group on Earth Observations Global Agricultural Monitoring Initiative), the other half of the G20's initiative. Operated by the University of Maryland, GEOGLAM monitors crop health via satellite observations.

Brazil's national agriculture agency, Conab, for example, became a GEOGLAM partner in 2018 and now incorporates these Earth observations into its national crop assessments provided to farmers. In Zambia and Zimbabwe, GEOGLAM works with the national agricultural ministries to create high-resolution cropland masks by combining Sentinel-2 observations with information crowdsourced from locals. By collaborating to build a food production information system based on high-quality Earth science and local expertise, farmers and everyone else along the food supply chain are gaining access to information that can help them prevent acute food insecurity before it strikes.

Field-level information products that incorporate remote sensing data are being developed by Kenya-based Pula. The company offers affordable insurance to small farmers across Africa and the Middle East. The insurance protects livelihoods when drought, floods, locust swarms, or other events damage crops or prevent germination. Locals use smartphone apps to report crop production information, which the company merges with geospatial observations. Pula then uses those apps to provide targeted agronomy consulting, as well as alerts about weather, pests, and disease. Pula reports that the number of insured farmers in Kenya has grown from 1,000 to 10,000 in about 3 years. The company has thus far paid out approximately US$766,000 for crop losses, and around 80% of households report using part of those insurance funds to purchase food.

Earth observations, of course, are useful only if they can provide meaningful information. Radiant Earth Foundation is developing machine learning methods to analyze and classify observations from the Sentinel-2 satellite. The organization is building an open library of spatially specific field data through partnerships, such as a data set of 319 farming plots in Kenya that combines Earth observations with on-the-ground surveys.

Coordination and engagement among these efforts is critical to improving our understanding of the Earth system and to providing real benefits to smallholders and the vulnerable communities they serve. Scientists engaged in these and other efforts to link Earth system science to food security outcomes should encourage further discussion across funding agencies, governments, universities, and scientists and work to bring in additional partners who can help deliver timely and reliable information, insights, and technology. The push to deliver more and better information about food security is literally a life-or-death proposition.

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Data Sets Are Foundational to Research. Why Don't We Cite Them?

Scientific researchers are instructed from the very beginning of their training about the importance of citing previously published literature and carefully documenting methods. We are taught that this corroborating information forms a solid foundation on which to rest our claims and conclusions. Citing data sets in the same manner, however, is another story. Although researchers have enthusiastically embraced digital data archives that can be shared and updated easily, they do not always cite data sets from these resources in their publications in ways that facilitate verification and replication of their results—or the assembly of metrics to gauge how the data sets are used.

Benefits of data set citation include improved reproducibility (particularly when the exact version of data used is indicated) and credibility of research, and clarification about the provenance and use of—and the proper credit for—data. Readers of scientific literature, including researchers, funding agencies, and promotional committees, rely on data set citation for information about data set usage. These metrics are extremely important in assessing the impact of a given body of work and of the facilities that publish and deliver data to the scientific community. Improper, incorrect, and incomplete data set citation hinders such assessments.

Publishers and data repositories have made significant progress over the past decade in increasing awareness of data set citation, and science policy bodies such as AGU have recommended the practice. Despite extensive awareness efforts by such groups, however, we observe a shortage of clear references to cited data in published scientific literature. We need a renewed approach to promote, educate about, and enforce citation of data sets in manuscripts—and to improve the specificity with which they are described.

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Collecting Data Set Metrics

Data centers like NASA's Earth Observing System Data and Information System Distributed Active Archive Centers (EOSDIS DAACs), which archive and distribute large amounts of environmental data, have been advocating the adoption of data citation for many years. EOSDIS DAACs use data set citation metrics, such as the number of times a data set has been cited each year and data sets that are commonly used together, to assess the use and impact of data sets they supply, consistent with the purposes of indices that track author citations [*Cook et al.*, 2016].

The Goddard Earth Sciences Data and Information Services Center (GES DISC), the National Snow and Ice Data Center DAAC (NSIDC DAAC), the Oak Ridge National Laboratory DAAC (ORNL DAAC), the Physical Oceanography DAAC (PO.DAAC), and the Socioeconomic Data and Applications Center (SEDAC) have developed processes for routinely collecting data set citation metrics by searching bibliographic databases and manuscripts.

Often, librarians at a data center's host institution collect data set citation metrics. Processes for this collection vary across data centers, but they all involve considerable and time-consuming manual effort, including searching for keywords and assembling citation records. Today a computer-extracted citation approach (using Scopus or DataCite) typically yields less than 60% of the record matches listed in a manual, librarian-assembled benchmark citation database. Automated approaches are improving, but they could be much better.

The lack of specificity in descriptions of data sets mentioned in published literature, the absence of data set references like digital object identifiers (DOIs), and the unavailability of robust open-source application programming interfaces (APIs) for scanning journal articles limit the adoption of automated approaches for collecting data set citation metrics. Scholarly literature search engines, such as Google Scholar, and the adoption of data set metadata standards for search engine optimization (such as the one offered by schema.org) have reduced the burden on data centers of collecting citation metrics for data archives. Machine learning techniques, open journal searches, wide adoption of data set DOI assignments, and improved DOI and data set specification in manuscripts will expedite the automated approach to data set citation metric collection.

Discovering Trends and Connections

The importance of data set citations has been widely reported in scholarly publications [*Piwowar et al.*, 2007; *Baggerly*, 2010]. In 2015, AGU released this statement affirming this importance: "Connecting scholarly publication more firmly with data facilities thus has many advantages for science in the 21st century and is essential in meeting the aspirations of open, available, and useful data" [*Hanson et al.*, 2015].

Data set citation metrics offer several advantages for data centers and producers as well as for data users and sponsors of data collection. By manually searching scholarly records and quality checking results, DAACs have assembled a time series database of data citation metrics, extending from 1997 to the present. The information collected includes DOIs and journal names of citing articles, as well as data set DOIs, the collection in which a data set is stored, and whether the data set was formally cited or simply acknowledged. Collecting citation information allows data centers not only to report metrics per data set but also to derive those metrics for project, data source, discipline, and other parameters.

Citation metrics can improve discovery of data sets by augmenting search indexes to highlight data sets related by citation.

Sponsors and members of research projects occasionally request citation metrics from data centers to gauge the impact of their research investments. Data centers also use citation information to understand linkages between various research domains. SEDAC, for example, has used data citation metrics to understand the interdisciplinary use of socioeconomic data with remotely sensed geospatial data in published studies. SEDAC uses this information to understand the impact of its published data sets in different application areas and sectors of society [*Downs et al.*, 2017]. Citation metrics can also improve discovery of data sets by augmenting search indexes to highlight data sets related by citation.

When references to all citations for a particular data set are available, end users can readily see common data-processing methodologies for those data, which may expedite and inform their own research. Citation records provide data centers with insights into patterns of usage and applications of data sets. This information is valuable in enabling data centers to provide improved services, such as data set-specific download services and increased relevancy of data set search results that best meet the needs of the user community.

Inadequate Acknowledgments

The challenges of collecting citation metrics notwithstanding, the advantages and importance of data citations are clear and well publicized. Unfortunately, data citation metrics are still not having the desired impacts.

As evidenced from data citation metrics starting from 1997, data sets are too often listed within the acknowledgments of published papers instead of as precise citations within a bibliography. When we analyzed the full catalog of publications from 1997 to 2019 included in the DAACs' citation metrics database, we observed that for any given year, 25%–80% of data sets used within published scientific studies are listed as citations. Although the range is not uniform across DAACs and years, the target is to improve the lower end of the citation range and come closer to our goal of 100% citation.

Practical limitations, such as word count, can prohibit detailed descriptions of data sets in manuscripts. However, we observe a lack of specificity about, and references to, data sets even when DOIs and robust citations are available. Mentions of data sets in manuscripts commonly lack information about the version of the data set used, the date it was accessed, the access end point (the location or URL from which the end user downloaded the data set), and spatiotemporal details (ranges in time and space to which the data apply). The vagueness in the data set mentions impedes provenance tracking and undermines the ability to reproduce results, which is a foundational principle of science.

In our analysis, we observed only a gradual trend in the adoption of data set DOIs and that less than 40% of the data citations provided the needed specificity about the data set used. In many cases, references to data sets were provided as generic references to a satellite, sensor, or project instead of to the location of the data. Statements such as "temperature data were downloaded from PO.DAAC" and "MODIS-Terra data were obtained from NSIDC," which do not provide sufficient details to pinpoint a data set, are distressingly common throughout the citation metrics database. Referencing data as being from the Terra satellite or the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, or from the Salinity Processes in the Upper Ocean Regional Study (SPURS) project, makes it very hard in most cases to trace the research methodology and analysis back to the source data sets. In this example, Terra, MODIS, and SPURS each have tens, if not hundreds, of data sets associated with them.

Vagueness in data set mentions impedes provenance tracking and undermines the ability to reproduce results, which is a foundational principle of science.

Without more specificity, librarians collecting citation metrics may have to read an entire article to determine the exact data set used, and even then, some ambiguity may remain. Also, librarians or other personnel may be able to associate data sets to an article only because of their specialized knowledge about the data sets, meaning that a reader of the article will not be able to identify with specificity or determine the provenance of the data set used in the article. The issue of association increases in severity for older publications.

Critical Fixes to Ensure Sustainable Data Citation

Two factors have brought us to an important crossroads with respect to data citation. First, data sets aren't being cited often enough and with enough specificity. Second, manual approaches for scanning, quality checking, and rigorously associating articles to data sets are becoming unsustainable. In light of the observed patterns described above, we need to act now to improve the citation of data in published literature.

We must maintain linkages between studies and the data sets upon which they are based to clarify research provenance and ensure that work is credible and reproducible. Without these linkages, many data sets will be undervalued and underused, and recognition of their contributions to science will be limited.

Clearly, the research community must acknowledge these issues and work to find immediate fixes. For starters, enforcement is needed for policies already in place, and new policies should be implemented. Only about half of journals provide a style manual for data citation. Journal publishers should expand the use of data citation to make it common practice and push more strongly for data citations to be comprehensive rather than concise [*Mooney and Newton*, 2012]. Journal publishers, editors, and reviewers should insist on this specificity and periodically audit their publications for data citation completeness. Such audits will help gradually shift current cultural norms. Enforcement can also come from scientists themselves as they promote expanded use of data set citations and call out instances of inadequate data attribution.

In addition, data centers must enhance their outreach and adopt additional tools and services to make data set citations prominent. For example, citation transformation service software that exports standardized citations from data sets to publishing tools like EndNote or LaTeX could simplify data citation. Recommended citation text should be made available alongside data sets at the point of data delivery, much in the same way that many journals provide "cite this article" links.

Acknowledging data set publication as a key research performance metric in research organizations and academic institutions will help increase awareness, use, and recognition of data sets. Such acknowledgments should, in turn, promote use of data set citations.

Research sponsors typically require regular status checks on the impact of data sets they fund. Increased use of data citations within publications should simplify the creation of metrics to evaluate the impact of data sets, similar to journal and author citation metrics, which could help facilitate status checks.

We are confident that with concerted efforts by the research community to adopt data set citations, we can very quickly observe a positive trend in the proper acknowledgment of data sets and in the specificity with which they are described in scholarly literature. By making these efforts, scientists will contribute to improving the provenance and reproducibility of research and thus to increasing its credibility and value.

Acknowledgments

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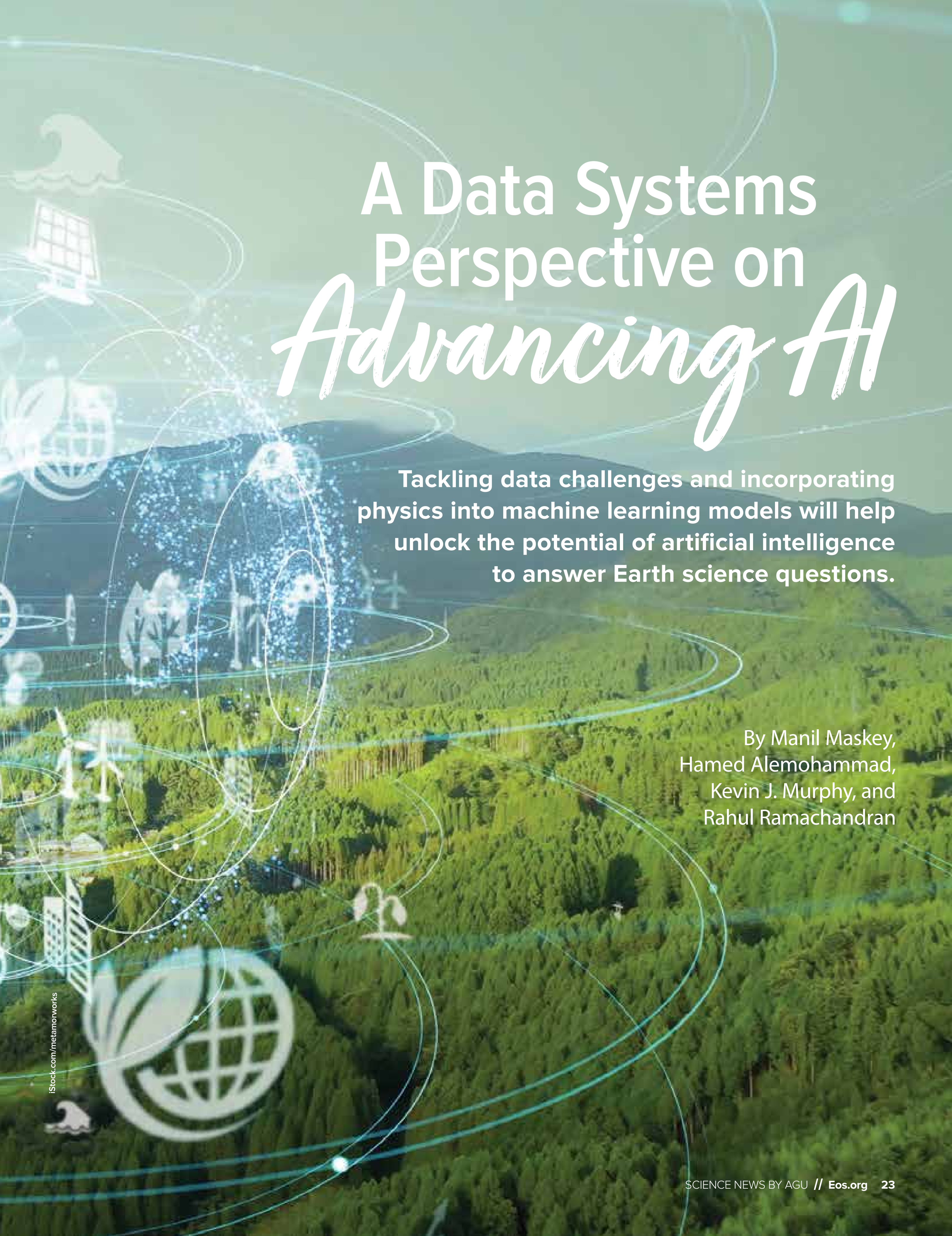

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A Data Systems Perspective on *Advancing AI*

Tackling data challenges and incorporating physics into machine learning models will help unlock the potential of artificial intelligence to answer Earth science questions.

By Manil Maskey, Hamed Alemohammad, Kevin J. Murphy, and Rahul Ramachandran

The Earth sciences present uniquely challenging problems, from detecting and predicting changes in Earth's ecosystems in response to climate change to understanding interactions among the ocean, atmosphere, and land in the climate system. Helping address these problems, however, is a wealth of data sets—containing atmospheric, environmental, oceanographic, and other information—that are mostly open and publicly available. This fortuitous combination of pressing challenges and plentiful data is leading to the increased use of data-driven approaches, including machine learning (ML) models, to solve Earth science problems.

Machine learning can discover patterns and trends buried within vast volumes of data that are not apparent to human analysts.

Machine learning, a type of artificial intelligence (AI) in which computers learn from data, has been applied in many domains of Earth science (Figure 1). Such applications include land cover and land use classification [*Jin et al.*, 2019]; precipitation and soil moisture estimation [*Kolassa et al.*, 2018]; cloud process representations in climate models [*Rasp et al.*, 2018]; crop type detection and crop yield prediction [*Wang et al.*, 2019]; estimations of water, carbon, and energy fluxes between the land and atmosphere [*Alemohammad et al.*, 2017]; spatial downscaling of satellite observations, ocean turbulence modeling [*Sinha*, 2019]; and tropical cyclone intensity estimation [*Pradhan et al.*, 2018], among others [*Zhu et al.*, 2017].

Machine learning uses a bottom-up approach in which algorithms learn relationships between input data and output results as part of the model-building effort, so it is not always easy to interpret the outputs of the resulting models. However, ML can discover patterns and trends buried within vast volumes of data that are not apparent to human analysts.

In traditional Earth science modeling, researchers use a top-down approach based on our understanding of the physical world and the laws that govern it. This approach allows us to interpret model outputs, yet it can be limited by the sheer amount of computing power required to solve large problems and by the difficulty of finding patterns where we don't expect them.

Recent efforts by Earth scientists have focused on integrating the best aspects of physics-based modeling and machine learning, incorporating physical laws into ML model architectures to help build models that are easier to interpret.

Complex Problems and Complex Models

Advances in ML and in its applications to Earth science problems have enabled us to tackle complex challenges [*Karpatne et al.*, 2019]. Machine learning techniques learn relationships among physical parameters from both input and output data, in contrast to traditional or physical modeling methods in which modelers explicitly account for those relationships when they set up a model.

Machine learning can involve either supervised or unsupervised learning.

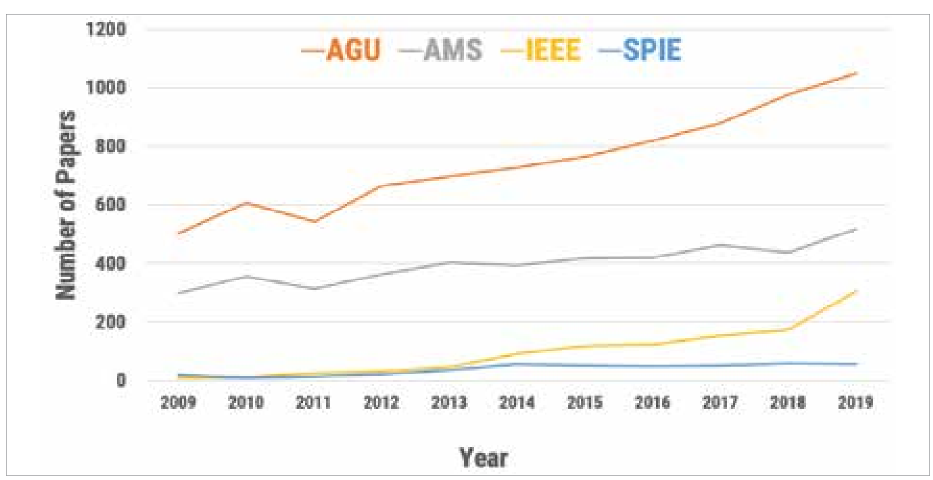

Fig. 1. The yearly number of Earth science papers from major publishers that discuss or use supervised machine learning. AMS = American Meteorological Society, IEEE = Institute of Electrical and Electronics Engineers, SPIE = International Society for Optics and Photonics. Credit: Katrina Virts and Rahul Ramachandran

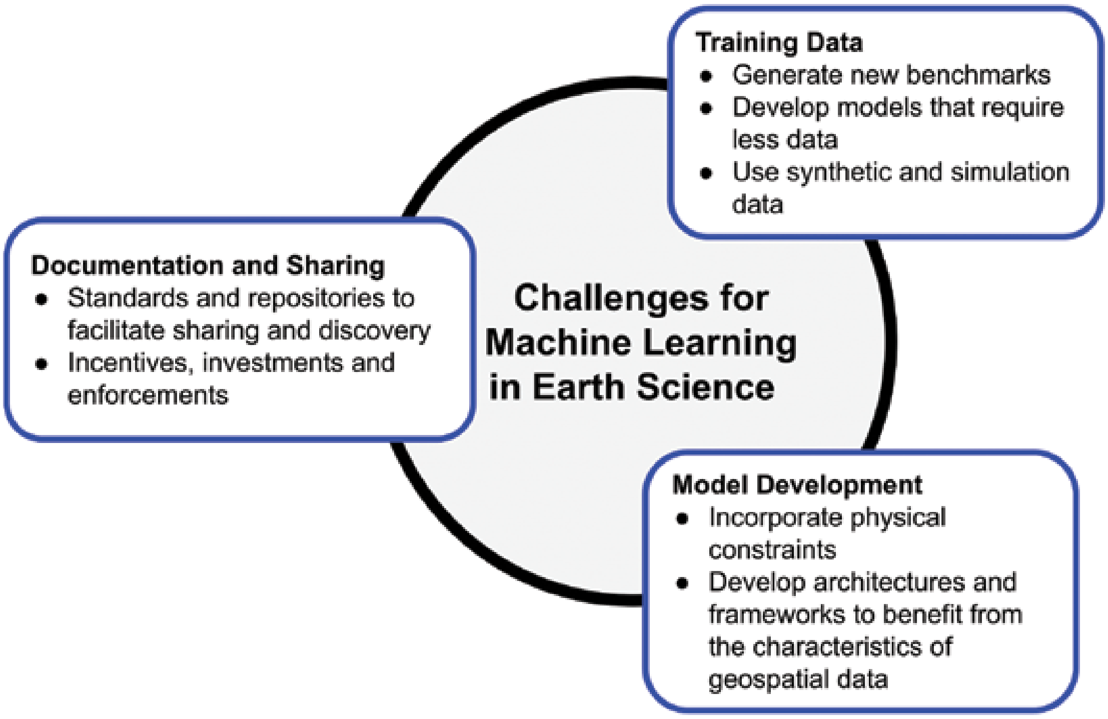

Fig. 2. Priority areas for using machine learning in the Earth sciences identified at a workshop hosted by NASA's Earth Science Data Systems Program and Radiant Earth Foundation. Credit: Hamed Alemohammad

Supervised learning techniques, which are especially useful in the Earth sciences, "train" ML algorithms using labeled data sets, which contain sample data that have been tagged with a target parameter. The algorithm can use an answer key to evaluate its accuracy in interpreting the training data. In unsupervised approaches, users feed unlabeled data to the algorithm, which tries to make sense of the data by extracting patterns on its own.

After training supervised ML models (i.e., estimating model parameters), applying the models to new data is fast and cheap. Speed and economy offer a distinct advantage over many physical models in Earth science, which must be inversely solved (causes are calculated from observed effects) and require significant time and computational resources for each application.

Numerical Models, Real-World Constraints

Interpreting ML model outputs and assessing why a model produces a specific output from a set of inputs can be difficult. However, the latest research shows that ML models can be combined with physical constraints to bridge the gap between data-driven methods and physical modeling and to increase the interpretability of ML models [*Reichstein et al.*, 2019; *Brenowitz and Bretherton*, 2018].

These advancements are encouraging; however, there are several challenges in adopting ML for the broader Earth science community (Figure 2). Specifically, high-priority challenges include

- a lack of publicly available benchmark training data sets across all science disciplines
- a lack of interoperability among data sources, types, and formats (e.g., standard data formats for computer vision algorithms may be different from the standard formats for commonly used Earth science models)
- limited availability of baseline pre-trained models that can be customized for various types or modes of Earth observations
- label or target values that are not usually structured, such as oceanic measurements from drifting buoys that cannot be adapted easily to the grid systems commonly used in ML algorithms

The Earth observation and ML communities would benefit from further collaborations to address these challenges and develop innovative solutions to geoscience problems. To promote such collaborations, NASA's Earth Science Data Systems (ESDS) Program and Radiant Earth Foundation hosted a workshop in January 2020 in Washington, D.C., that gathered 51 scientists, practitioners, and experts from government agencies, nonprofit organizations, universities, and private industry. Workshop participants presented and discussed

Machine learning models can be combined with physical constraints to bridge the gap between data-driven methods and physical modeling and to increase the interpretability of ML models.

> **Because extreme weather events and impacts of climate change are rare or unseen in training data gathered from historical observations, machine learning models usually struggle to provide accurate predictions of scenarios involving such events or impacts. human analysts.**

recent advances in ML techniques as well as their applications to Earth science problems.

Three working group sessions reviewed existing gaps in knowledge and tools, and they provided recommendations to facilitate applications of ML to Earth observation data. In particular, participants created a set of recommendations to develop an ML "pipeline" involving training data generation, model development and documentation, and sharing these models and data sets. The full report from the workshop is available online at bit.ly/ML-meeting.

A Need for Training Data

Generating and publishing benchmark training data sets that researchers can use to build better models are key to accelerating ML innovation. The shortage of available training data is the main bottleneck in advancing applications of ML in the Earth sciences. These data are used to estimate model parameters and are thus the building blocks of an ML model. But generating new training data sets is an extensive and, in some cases, expensive process.

Because of the importance of training data, new investments are required to support existing efforts focused on training data generation and maintenance. These investments should focus on broadening the availability of training data sets that represent the diversity of problems within relevant science disciplines.

NASA ESDS has already invested in its competitive programs to generate high-quality training data sets that are open and easily shareable. ESDS has also started to invest in challenges to develop benchmark models for existing training data sets. ESDS policies require the resulting training data sets, models, and source code to be open and free for public use.

It is also essential to increase research and investment in techniques such as active learning and semisupervised learning, which require less training data than supervised ML approaches. Other avenues for potential innovation involve the use of synthetic training data generated by models (in contrast to using observations) and the use of training data from physical model simulations.

Complicating the effort to construct ML training data sets is the fact that Earth science data have diverse properties that are not always consistent or interoperable. Satellite observations and models, for example, provide multiband and multimode data that do not always include the three spectral bands typical for imagery data in the computer vision community. And ground observations are sometimes captured in a Lagrangian reference system—in which the observer follows an individual particle as it travels through space and time—rather than the common Eulerian system, in which the observer remains stationary. To use these data in ML models properly, new architectures and frameworks must be developed and adopted by the community.

Physically Aware Machine Learning Models

Because ML techniques learn patterns from data and do not incorporate physical laws (e.g., mass and energy balance), they typically cannot extrapolate beyond the range of parameters learned from the training data set used. The inability to extrapolate is a challenge for expanding ML-based applications in the Earth sciences. For example, because extreme weather events and impacts of climate change are rare or unseen in training data gathered from historical observations, ML models usually struggle to provide accurate predictions of scenarios involving such events or impacts [*Rasp et al.*, 2018].

In recent years, several approaches have been implemented to embed physical constraints in either ML model architectures or the cost function (which helps the model make itself more accurate) during training. These approaches have shown promising results in estimating atmospheric convection, sea surface temperature, and vegetation dynamic modeling. Further research is needed to build and expand physics-aware ML models in the Earth sciences.

Documentation and Sharing

Machine learning research benefits from fast iterations (i.e., rapid fitting and tuning) on various model architectures and data features. Enabling innovation in this field therefore requires thorough and proper documentation as well as sharing training data sets and models so that different researchers can trace and replicate the work others have done. Workshop participants highly recommended following the FAIR (findable, accessible, interoperable, and reusable) data management principles for cataloging ML training data and models.

Machine learning model and training data catalogs should include sufficient metadata in a standard format to facilitate their discovery and retrieval. Existing data catalog standards, such as the SpatioTemporal Asset Catalog, work well for and enable cataloging of various types of geospatial data. But more research is needed to overcome limitations of such standards for use in such cases as storing nonraster data (data stored as vectors rather than in rows and columns). Moreover, the research community needs to adopt similar catalog standards for storing ML models to streamline model sharing among different groups.

Incentives and Investments

As a result of the 2020 workshop, the assembled members of the Earth observation and ML communities made recommendations for meeting challenges in adopting and accelerating ML in the Earth sciences.

To further facilitate sharing of data sets and models, incentives should be provided to researchers and developers, and new investments are needed to support collaborative efforts for developing and maintaining open-source scientific software. Incentives may include recognition by the researchers' organizations (especially at academic institutions), legal support to ensure intellectual property rights and proper use of their work by others, and proper citation mechanisms. Investment may be in the form of grants that specifically support development and deployment of applications and open-access training data and models. Stricter policies for sharing training data and models by scientific journals and funders are essential as well.

If these recommendations are accepted and acted upon, we are confident that the continued application of ML to the wealth of Earth observation data available will produce answers for many pressing questions and problems in Earth science facing us today.

Acknowledgments

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An innovative program focused on collaboration and capacity building is looking to improve outcomes for smallholder farmers, reduce hunger, and alleviate food insecurity in sub-Saharan Africa.

SOWING SEEDS OF FOOD SECURITY IN AFRICA

By Catherine Nakalembe, Christina Justice, Hannah Kerner, Christopher Justice, and Inbal Becker-Reshef

A farmer weeds her field in Morogoro, Tanzania. Credit: Catherine Nakalembe

Food security is one of the most pressing issues, if not the most pressing, faced by many African countries today. And events in recent years have increasingly strained food supplies for populations in sub-Saharan Africa. In 2019, Cyclones Idai and Kenneth ravaged southern Africa and coincided with droughts, extreme flooding, and landslides in southwestern and East Africa [*Nakalembe*, 2020], all of which devastated smallholder farmers.

Last year brought further shocks and setbacks to crop production across Africa. Farmers in East Africa, for example, faced more devastating floods, the most severe (and still ongoing) desert locust infestation in 70 years, and, of course, the COVID-19 pandemic, which has affected every sector and every food system and has brought global food security into the limelight.

COVID-19 disproportionately affects the most vulnerable communities, but it is also affecting previously food secure communities. In 2019, food insecurity already affected nearly 690 million people globally, and by the end of 2020 more than 100 million people were projected to become food insecure because of negative economic consequences attributable to COVID-19 [*Food and Agriculture Organization of the United Nations et al.*, 2020]. With the number of food-insecure people worldwide projected to exceed 840 million by 2030 [*Nakalembe*, 2020], we are certainly not on track to achieve the United Nations' "Zero Hunger" Sustainable Development Goal.

In sub-Saharan Africa, agricultural system shocks in coming years will continue to have severe impacts on the food security of smallholder farmers. Analyzing the nature and extent of these impacts and assessing their significance on livelihoods are important in planning responses and mitigation efforts, but these can become overwhelming tasks with only conventional capabilities like on-the-ground observations and surveys of farmers. Satellite-based Earth observations (EO), which provide crucial information about crops in near real time, can play a vital role in supplementing such capabilities, enabling earlier warnings of disasters and supporting response programs involving risk financing and other measures that reduce food insecurity.

IN SUB-SAHARAN AFRICA, AGRICULTURAL SYSTEM SHOCKS IN COMING YEARS WILL CONTINUE TO HAVE SEVERE IMPACTS ON THE FOOD SECURITY OF SMALLHOLDER FARMERS.

Harvest is a NASA Food Security and Agriculture program that seeks to strengthen food security by producing and distributing relevant and actionable information on agricultural conditions and production outlooks at national, regional, and global scales. In particular, the Harvest Africa initiative is spearheading the uptake and integration of EO data by national and regional agencies to support decisionmaking and to benefit food security, agriculture, and human and environmental resilience in Africa. Harvest Africa has prioritized four pillars to achieve its goals:


A farmer guides a data collection team during fieldwork in Njombe, Tanzania. Credit: Catherine Nakalembe

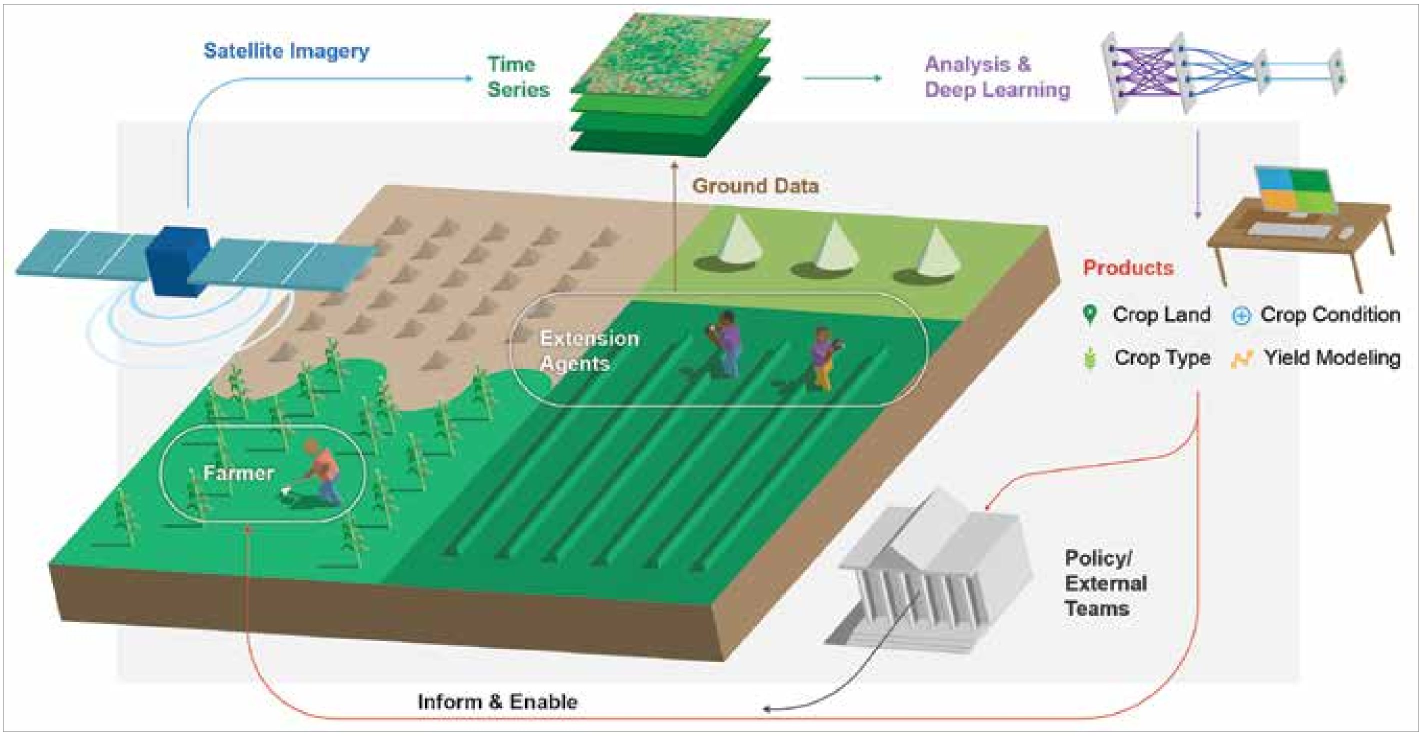
1. Improving monitoring and early-warning systems that provide actionable data and information about agricultural productivity and food security at multiple scales
2. Advancing methods that underpin the relevant EO data and systems
3. Developing and transferring capacity to national and local users in Africa who influence decisionmaking
4. Developing strong, long-term, sustainable partnerships

EO-Based Monitoring

With heightened uncertainty about the numerous threats to crop production today, like increased flooding, drought, and pest infestations, there is a need for more frequent and detailed agricultural reporting to inform international consensus as well as responses at regional and national levels. This information can reduce speculation about crop production and food availability and provide early warnings of potential production shortfalls, which are especially critical for regions at high risk of food insecurity.

Harvest supports these needs through its role in the international Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM). Harvest coordinates the GEOGLAM Crop Monitor for Early Warning (CM4EW), which provides timely, science-driven information on global crop conditions. This information comes from satellite-derived indicators of vegetation conditions (based on the normalized difference vegetation index), precipitation, temperature, soil moisture, evapotranspiration, and runoff. CM4EW also facilitates information exchange across the international community, building consensus among major agricultural monitoring agencies [*Becker-Reshef et al.*, 2020], reducing uncertainty in global crop condition assessments to support agricultural and humanitarian decisionmaking, and synthesizing these consensus assessments into monthly bulletins.

In East Africa, at the national level, the Crop Monitor has been adapted and adopted for full operational use by national ministries in Kenya, Tanzania, and Uganda, and it is currently in development for use in Mali and Rwanda. And regionally, the Intergovernmental



NASA Harvest and its partners, including local extension agents, combine and analyze satellite and on-the-ground data using innovative products like machine learning to create maps and other data products that can inform agricultural policy and responses to food security concerns at regional, national, and local levels. Credit: ©University of Maryland 2020, all rights reserved

Authority on Development, which represents eight East African countries, has led the East Africa Crop Monitor through its Climate Prediction and Applications Centre (ICPAC). This system has become a leading data source for food security information that complements and contextualizes ICPAC's seasonal climate forecasts.

Harvest is also leading the development of a NASA Harvest COVID-19 Price Monitor Dashboard and coleading an international locust monitoring working group. The dashboard incorporates different EO data sets and market information to help draw useful connections between COVID-19 impacts on agricultural production and their effects on markets at various scales. The locust working group has supported the development of critical EO data sets needed for monitoring the ongoing locust invasion in East Africa.

Developing Improved Methods

EO-based monitoring systems and decisionmaking with respect to agriculture and food security rely on accurate and up-to-date products such as maps of land cover and crop type, conditions, and yields. Harvest is developing new methods to improve these products, using machine learning, biophysical and agroecosystem models, and statistical techniques. To promote the operational uptake and sustainability of these new methods, Harvest is codeveloping methods with stakeholders from the outset and is making models and data sets publicly available whenever possible.

For example, we have developed a new method (a multiheaded long short-term memory, or LSTM, model) for postseason and in-season crop classification using deep learning in combination with satellite data from Landsat 8, Sentinel-2, and Sentinel-1, as well as with commercially available fine-resolution data from Planet Labs [*Kerner et al.*, 2020]. The LSTM learns from global and local training data to detect crops in multispectral time series data.

Products created with this method, such as 2019 cropland maps for Togo and 2019 and 2020 in-season maps for Kenya, provide decision-makers with trustworthy information on where crops are growing and how those crops are performing. The Togo map, for example, provided information about the size and location of croplands that census data might have missed. It also supported Togo's YOLIM program, an interest-free digital loan program designed to boost food production across smallholder farms by funding the cost of farming essentials like fertilizers, pesticides, and tractor rentals.

As there are few publicly available training data sets for crops in smallholder regions in Africa, our machine learning models are being designed to leverage diverse, global crop data sets to augment this sparse availability while still being tailored to account for regional differences in growing practices, crop calendars, and other factors [*Becker-Reshef et al.*, 2020; *McNally et al.*, 2017]. We are also addressing the scarcity of training data by working with organizations and extension agents in partner countries and by developing methods to scale and sustain ground data collection. Harvest researchers, for example, have trained networks of extension agents and students in Mali, Tanzania, and Uganda who collect ground data in partnership with Lutheran World Relief in Mali, the Office of the Prime Minister in Uganda, and Sokoine University of Agriculture in Tanzania. Harvest is also set to lead a Lacuna Fund project called "Helmet Labeling Crops" in five countries to deploy a rapid semiautomated approach to developing an unprecedented training data set for machine learning applications.

Catherine Nakalembe (right) works with an extension agent in Iringa, Tanzania, to fill in a data collection form. Credit: Christina Justice

Reaping Worldwide Recognition

Since November 2017, NASA Harvest has initiated or been involved in roughly 30 projects around the world to improve tools and grow regional and local capacity to address food insecurity. This work has garnered well-deserved acknowledgment. Harvest Africa received global recognition in 2020 when its program director, Catherine Nakalembe, was selected as a 2020 Africa Food Prize laureate for her dedication to improving the lives of smallholder farmers through the use of satellite technology to harness data and guide agricultural decision-making. Harvest team member Hannah Kerner was included on Forbes's "30 Under 30" list in science this year, and Christopher Justice, Harvest's chief scientist, received a NASA Distinguished Public Service Medal. Moreover, the United Nations World Food Programme, a Harvest partner, received the 2020 Nobel Peace Prize for its efforts to combat hunger globally and improve conditions for peace.

IT IS MORE CRITICAL THAN EVER FOR RESEARCHERS TO USE THE TOOLS AND RESEARCH AVAILABLE TO HELP GOVERNMENTS AND ORGANIZATIONS WORKING TO MITIGATE THE NEGATIVE EFFECTS OF FOOD SYSTEM SHOCKS.

Building Capacity in Africa

Harvest Africa has invested heavily in capacity building to advance how crops are monitored in sub-Saharan Africa and to ensure that EO systems and methods are responsive to user needs and are filling critical data gaps. To do this, we have focused on melding local knowledge, resources, and expertise with our own to better understand existing problems and to help identify and prioritize institutional needs.

We have also worked with our national partner organizations to enhance their capabilities to access and use available data and resources and to prevent project frame failures and unintended consequences of half-baked solutions, such as short-term projects that end too suddenly or the implementation of systems that are not fit for purpose. Our approach also links our partners with the broader EO and development community, further enhancing capacity through exposure to the skills and experience of other researchers and organizations.

The result of these capacity-building efforts is that there are now networks of trained Crop Monitor "champions" who are versed in making EO-based assessments of crop conditions. These champions lead national efforts and participate in regional Crop Monitors, and they contribute to the CM4EW, bringing critical national-level insights to the global context. As noted above, extension agents also provide valuable ground-based data and information, so that even in 2020, when travel restrictions made it impossible for national and international experts to carry out ground assessments, we had means of reliable data collection and sharing.

Networks and Partnerships

By design, NASA Harvest is a partnership of partnerships—a multidisciplinary and multisectoral consortium of leading scientists and agricultural stakeholders in both public and private organizations. In Africa, we have partnered with government departments, nonprofits, and international development organizations to improve outcomes for end users. These partnerships have proven essential in ensuring access to critical technical expertise and EO and ground-based data sets and in facilitating and funding training events.

In response to a request from the government of Togo, for example, NASA Harvest worked with Planet Labs to access very high resolution data needed to generate the high-resolution cropland map that the government used to support its YOLIM program.

Officials from Tanzania's Ministry of Agriculture examine field boundary delineations to be used in an agriculture monitoring scheme. Credit: Catherine Nakalembe

A satellite-based Global Agriculture Monitoring system developed by the University of Maryland in partnership with NASA and the U.S. Department of Agriculture was customized for East Africa, enabling implementation of the World Bank's Disaster Risk Financing and Insurance Program. In Uganda, this program has supported more than 300,000 individuals in the Karamoja region, providing alternative livelihoods to smallholder farmers affected by drought.

Extending the CM4EW system to Kenya and Rwanda, meanwhile, was achieved through direct collaboration between Harvest and the multination Regional Centre for Mapping of Resources, with support from the NASA- and U.S. Agency for International Development–sponsored SERVIR program.

And in yet another example, a partnership with Lutheran World Relief in Tanzania directly led to the Relief to Resilience project in Mali, which is strengthening the early-warning system there by increasing the capacity of government agencies to monitor crop conditions using EO data. This improvement in turn contributed to the development of the Mali Crop Monitor, which has been integrated into Mali's early-warning reports.

A Call to Action

The COVID-19 pandemic along with ongoing climate- and weather-related extremes presents unprecedented challenges for food security, in Africa and elsewhere, that we are yet to fully understand. But there are opportunities to use EO to help address these challenges. It is more critical than ever for researchers to use the tools and research available—and for these tools and data to be openly accessible—to help national governments and organizations working to mitigate the negative effects of food system shocks. Prioritizing smallholder farmers in this effort is particularly vital because it is abundantly clear that these farmers cannot be ignored if we are to end hunger for everyone [*Nature*, 2020; *Laborde et al.*, 2020].

The Harvest team is continuing to put the best information and tools into the hands of decisionmakers and, ultimately, smallholder farmers. And the science-driven and actionable research, national-level capacity building, and global coordination via the GEOGLAM Crop Monitor that Harvest coordinates are offering earlier and more accurate warnings of potential threats to crop production and food security.

This work is translating research into tangible, positive outcomes for farmers and communities vulnerable to food insecurity. Through such open science and coordination among local, national, and international groups, we can leverage everyone's combined knowledge and resources and make systematic and measurable progress toward ending hunger.

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CLIMATE CHANGE *UPROOTS* GLOBAL AGRICULTURE

Climate change is shifting where ideal growing conditions exist and is leaving farmers behind. How can we secure our future food supply and support the people who grow it?

By Kimberly M. S. Cartier

In much of the world, climate change is altering regional growing conditions and making them more unpredictable. Farmers are finding it harder to consistently grow enough food to meet increasing demand. Securing the world's food supply for the future, experts assert, requires us to tally the good and the bad in the current agricultural structure, including the infrastructure and technology in food distribution systems.

Small farms, which account for about 90% of the world's 570 million farms, are particularly vulnerable to changes in seasonal climate. Land tended by families for generations may suddenly become nonarable. A change in the timing or intensity of yearly rainy seasons or the El Niño–Southern Oscillation (ENSO), for example, could bring rains or drought that wipe out a family's crops.

In early May 2020, the Nzoia River burst its banks. The floods that resulted in western Kenya capped off particularly heavy long rains that killed 237 people and adversely affected more than 800,000. Floods and landslides destroyed homes, schools, roads, bridges, and more than 8,000 acres (32 square kilometers) of Kenyan farmland.

Kenya's March–May rainy season (the long rains, as opposed to the short rains of October–December) provides vital moisture to the country's croplands—indeed, maize production was at least 10% above average in 2020—but most Kenyans continue to face some level of food insecurity. In the past few years especially, climate change has caused a geographical shift in which areas receive rain and which suffer drought.

"Normally, we know where the flood areas are," but the rains the past few years have been "unprecedented," said Ruth K. Oniang'o, founder of the Rural Outreach Africa Program and a 2017 Africa Food Prize Laureate. "We have rain falling in areas that never used to have rain. I used to write all the time about famines and drought… but right now is something different. We can say, 'Okay, climate variability, it changes every year.' No. This is different right now."

The differences extend beyond Africa. Farmers in Iran, for example, share similar problems anticipating cycles of drought and floods despite being separated from their Kenyan counterparts

Sadcha Somkhuan / Alamy Stock Photo

"OFTEN YOU SEE CLIMATE CHANGE ACTING ON TOP OF THIS CLIMATE VARIABILITY AND EXACERBATING STRESSES THAT ARE ALREADY EXISTING IN OUR FOOD SYSTEM."

by more than 7,000 kilometers. "The recent harsh droughts and heavy floods in the [Middle East] region ruined a major part of food resources," explained Mohanna Zarei, a water resources engineer at the University of Kurdistan in Sanandaj, Iran. Sporadic precipitation cycles not only reduce crop yields but can also lead to secondary impacts that worsen food security, like the wildfires that have ravaged thewestern United States, Australia, Brazil, and elsewhere.

Financial and social inequality compound climate-related food security issues. Many of the world's smallholder farmers are poor and food insecure; even one lost season can push them from struggling to failing. "Climate change plays a key role as a catalyzer" in amplifying preexisting resource problems and "will influence the quality and quantity of food we produce and our ability to distribute it equitably," Zarei said.

"It's not quite as simple as moving into less climate-affected areas. It remains an issue of climate and socioeconomic and technological development," said Weston Anderson, a hydroclimatologist at the International Research Institute (IRI) for Climate and Society at Columbia University in Palisades, N.Y. Understanding how agricultural practices and policies need to change along with the warming climate and then sowing the seeds of that change could be the difference between farmers thriving where they are or migrating to greener pastures.

Stressing the Climate System

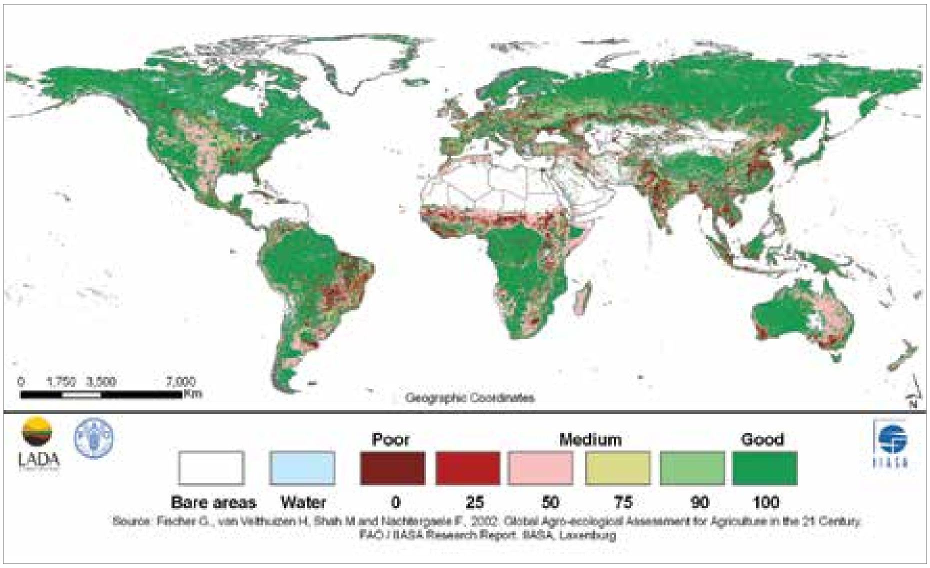
A region's agricultural stability depends on reliable, natural climate variations to bring seasonal shifts in weather. Large-scale climate modes like ENSO and the Indian Ocean Dipole govern a region's temperature, precipitation, and storm activity for months at a time. Climate modes also causally connect distant regions, something that has been increasingly important as agricultural trade has become more global: A climate shift in one food-growing region can also affect crops half a world away.

Maize farmers around the world felt the impacts of climate teleconnections during one of the strongest El Niños of the past 150 years. The 1983 El Niño coincided with the largest global synchronous failure of maize crops in modern record, and recent research has shown that ENSO played a major role in causing that failure.

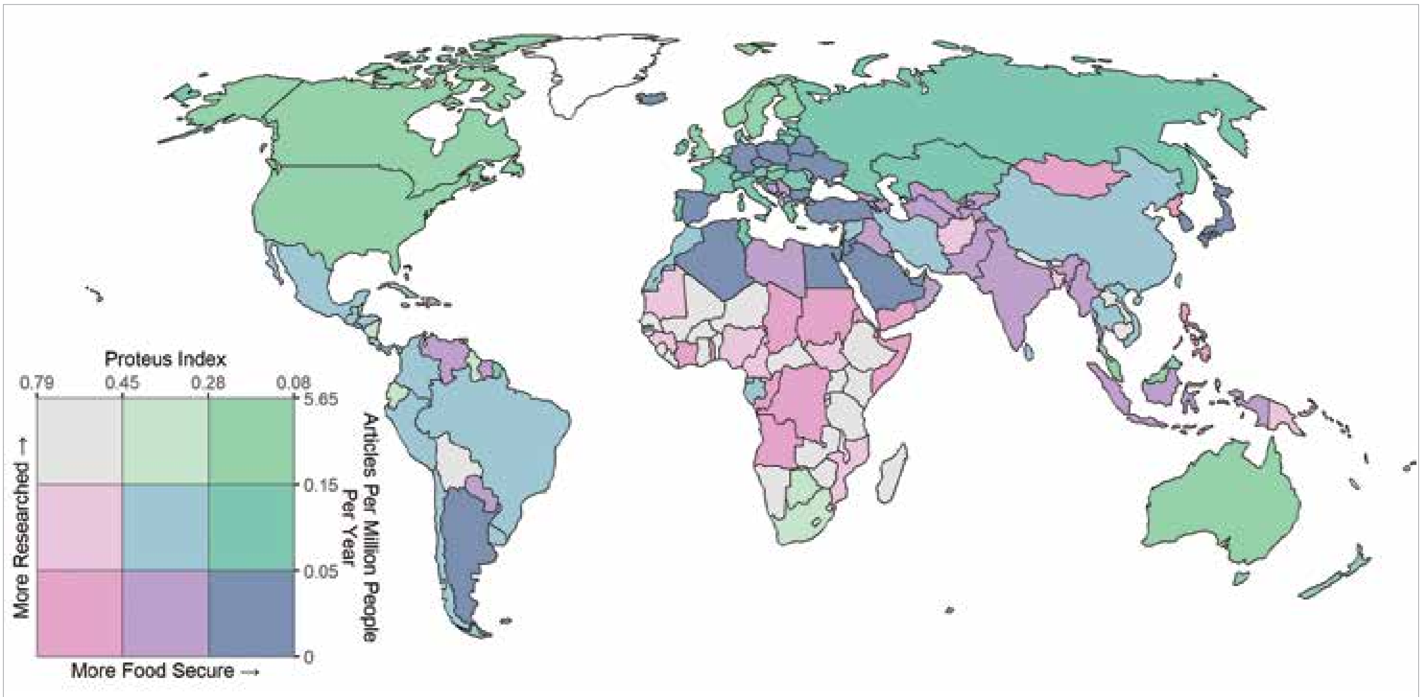
"The El Niño–Southern Oscillation, because it organizes global weather and global precipitation, provides structure on the risk of global agriculture by rearranging where we get more drought and less drought in the year," Anderson explained. "It's not necessarily creating more drought over the entire year, but it might be arranging those droughts in a way that disproportionately affects some of our crop growing regions."

Anderson's team found that ENSO is the only mode of climate variability that can affect maize, wheat, and soybean crop production on a global scale. Other large-scale climate modes have more localized influence on certain crop yields. The tropical Atlantic variability, for instance, influences maize production in western Africa and wheat and soy production in southeastern South America simultaneously, but the North Atlantic Oscillation affects only wheat production in northern Africa and Europe.

"Climate will largely continue to affect our food system through climate variability," Anderson said. "Often you see climate change acting on top of this climate variability and exacerbating stresses that are already existing in our food system." For example, he said, a regional crop might withstand a normal ENSO-related drought but could fail if climate change-induced drought worsens, too.



The health of the soil beneath vegetation, called relative soil health, is a fundamental aspect of food security. According to the Food and Agriculture Organization of the United Nations, roughly one third of the world's soils are moderately degraded (pink) or in worse condition (red and burgundy). Regions that maintain good (green) or only slightly degraded (yellow) soils are, for the most part, uncultivated. Credit: © FAO



Areas addressed in the current body of food security literature are not evenly spread across the globe. Some regions are overrepresented despite having high food security (bright green), whereas many food-insecure areas are underrepresented (bright pink) and need more attention. Regions with low food security that are well represented by current research practices (gray) likely have preexisting infrastructure to support academic research, like in eastern and western Africa. Credit: Cooper et al., 2020, https://doi.org/10.1016/j.gfs.2020.100392, CC BY 4.0 (bit.ly/ccby4-0

Down in the Dirt

Moreover, climate change also affects what goes on beneath Earth's surface. To sustain an agricultural system with consistent, high, and high-quality yield, "you need the soil system to first and foremost be able to support plants," said Asmeret Asefaw Berhe, a soil biogeochemist at the University of California, Merced. "Plants need physical support from the soil, and they also need nutrients and water to be available in the right forms and in the right time when plants need them."

According to a 2015 report from the Food and Agriculture Organization of the United Nations, about one third of the world's soil is moderately to highly degraded, and the conditions causing that degradation are, overall, getting worse. Unsustainable agricultural practices cause some of the decline in soil health, and some is caused by climate change, Berhe said. "Hot temperatures, for example, are associated with rapid loss of organic matter from soil. This is a major issue, as organic matter is the major storehouse of food and energy for microbes in soil that are key for regulating nutrient availability."

Moreover, "the episodic high-intensity rainfall, wet periods, and droughts, the going back and forth between extremes, could also lead to conditions where soils are actually eroding at a fast rate, especially under intense precipitation events," Berhe added. "That's a major concern." Altered rainfall patterns can also unbalance a soil's oxygen availability, acidity, salinity, and water-holding capacity and can hinder the formation of new soil.

"Climate change reshapes the relationships among crops, pests, pathogens, and weeds," Zarei said, "and it intensifies several trends, including declines in pollinating insects, increasing water scarcity, increasing ground-level ozone concentrations, and fishery declines. Climate change [has] posed pressures on availability of water resources for agriculture by shifting precipitation patterns, earlier seasonal snowmelt, and intrusion of saltwater into coastal aquifers."

It is true that some areas of the world are becoming more arable in the face of climate change, especially the Arctic. The warming planet pushes the agricultural frontier poleward and into carbon-rich areas of thawed permafrost and peatland. "The climate envelope moving means that certain areas are now able to support different types of habitats," Berhe said. "But I think it's a little hard to call that improving soil health because of the way we got there."

"A northward shift in where we grow foods commercially is one of the most likely new agricultural frontiers," said Merritt Turetsky, and "the cost of imported foods in the Arctic can be exorbitant." Turetsky is an ecologist at the University of Colorado Boulder and a science adviser for *Eos*. "Could an increase in commercial or local food production at high latitudes solve this problem of high food prices? Maybe, but it is likely to introduce some complex challenges for northern regions and the people who depend on those lands."

Declining soil health around the world also encourages governments to cultivate untouched ecosystems, which can worsen environmental problems in the long run. For example, "we know that drainage of tropical peatlands for palm oil production has released large amounts of stored peat carbon to the atmosphere," Turetsky continued. "As a society, we must protect our northern peatlands and carbon-rich soils from drainage and cultivation."

Short-Term Fixes Make Long-Term Problems

When it comes to humanity's role in the decline in soil health and the growing unpredictability in crop yield, some aspects are out of farmers' hands: rapid urbanization, inefficient infrastructures, unstable political relations, war. Problems like widespread poverty, hunger, government corruption, gender inequality, and lack of education multiply food security issues around the globe.

However, some of the ways in which farmers mitigate agricultural uncertainty, which may raise short-term yields, actually worsen growing conditions in the long run. The lands' "ability to provide the food, feed, and fiber that we were getting from them is getting compromised," Berhe said. "And so the only way to keep the lands productive, then, is to keep pumping them full of supplements in the form of fertilizers, in the form of irrigation water, in the form of tilling them even more destructively" than we do now.

When crop yields go down, farmers try to expand into new land. "But sometimes extending into other areas means that people are now working on marginal lands that we know are susceptible to degradation," Berhe explained. Marginal lands often already have poor soil or are prone to erosion. "That could play out in very disastrous ways when people move away from their home or expand their production systems."

Too, lands might be marginal because they are wet, Turetsky added, and wetlands and seasonally flooded lands tend to store more carbon than more productive lands do. "This means that extending agricultural practices can release more greenhouse gas to the atmosphere as those new soils are disturbed."

The use of fertilizer can also cause significant long-term environmental damage. "The issue of fertilizer is a central concern in the Senegal River valley," said Mor Ndiaye, an agricultural engineer and soil scientist who works with smallholder rice farmers in the valley. Ndiaye works at SAED, an organization that promotes sustainable agriculture in Saint-Louis, Senegal.

"As the use of fertilizer in agriculture has become more and more essential, however, the quality of the soil is not very often taken into

Irrigated cultivation of rice paddies, seen here, accounts for roughly 70% of Senegal's total annual rice production. Developing sustainable irrigation infrastructure has governed much of the agricultural growth in recent decades and will continue to play a key role in our future food security. Credit: Africa Rice Center, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

“MANY GROWERS BELIEVE THAT INCREASING THE AMOUNT OF FERTILIZER IS SYNONYMOUS WITH GOOD YIELD.

account when it comes to the purchase of fertilizer by farmers [and] producers,” Ndiaye said. “Many growers believe that increasing the amount of fertilizer is synonymous with good yield.”

However, “adding nitrogen fertilizers into agricultural areas is one of the most important causes of nitrous oxide emissions to the atmosphere and the one that we have the hardest time taming,” Berhe said. Nitrous oxide is the third most prevalent greenhouse gas. “It’s a pretty vicious cycle.”

A lack of data also crops up as a problem when trying to secure agricultural production. Remote sensing data via satellite can provide environmental information like temperature, moisture, and plant cover, but it has data gaps. “Often, remote sensing can get us 90% of the way there,” said Matthew Cooper, an environmental geographer at the Harvard Data Science Initiative in Cambridge, Mass. “You do need a lot of ground data to validate the remote sensing variables. Measuring the actual rainfall on the ground or measuring actual crop yields on the ground will always be more accurate than what you’re trying to estimate from space.”

Moreover, smallholder farmers are more likely to thrive if they can analyze soil samples before buying and cultivating new land, but those data “are sometimes difficult to obtain given the often exorbitant cost,” Ndiaye said.

And satellites can’t collect data on “things related to food systems around trade and access” like market prices, Cooper said. However, many governments lack resources for on-the-ground data collection initiatives as they tackle more immediate concerns, or as they attempt to mask the extent of environmental problems, for example, as has happened with deforestation in Brazil.

Cultivating a Food Secure Future

The agricultural market has become irreversibly global, and with most nations far behind on climate goals, the impact of climate change on farmers is unlikely to abate. What can geoscientists do to support more sustainable agriculture in current food-growing regions and maintain soil health in new growing areas?

In some of the most food-insecure regions of the world, it’s difficult to pinpoint what actions are needed because food security research simply doesn’t cover those areas. According to a recent study that text mined more than 16,000 abstracts from the food security literature, some of the most food-insecure regions of the world have very little presence in food security research, whereas some regions with high food security are overrepresented. “Researchers tend to cluster in the countries where you’re not at risk of a sudden civil war or there are already established research institutions or where people have already built full careers,” said Cooper, who was the lead researcher on the study. In more unstable areas, “local policymakers there are pretty well informed of the local situation but…it seems like places outside the Anglosphere are less visible to the global community.”

Improving data access is key. Even without on-the-ground data networks, “we can tell a ton of stuff, especially about anything environmental, from remote sensing,” Cooper said. “You can get indices of vegetation health, precipitation, rainfall, droughts,” but that information needs to make its way to farmers in a way they can use.

Work like Ndiaye’s helps connect smallholder farmers in developing agricultural areas with high-level data products like digital soil maps. Access to that information has helped rice farmers in the Senegal River valley strengthen the capacity of their agricultural sector and establish trade partnerships between farmers, suppliers, and buyers.

Most experts agree that water availability will continue to be a bottleneck in expanding current agricultural areas and establishing new ones. “Irrigation uses 66% of annual water withdrawals and is the single largest human use of water,” Zarei said. But in some areas of the world, including some Middle Eastern countries, she explained, water resources are being used as political leverage rather than as a common resource to support regional stability.

Moreover, the past 70 years or so have seen “something like a 200% increase in irrigated agriculture area,” Anderson said, “and around 50% of that is not sustainable in the sense that we’re drawing irrigation water unsustainably from either surface water or groundwater.”

Cities like Aqaba, Jordan; Bangkok, Thailand; Kampala, Uganda; Lima, Peru; and Manila, Philippines, have shifted to more sustainable water usage “by reusing their wastewater and using this recycled water in the energy sector, food industry, agricultural irrigation, water sector [and] transitioning to a circular economy,” Zarei said.

Looking back at agricultural production since 1950, Anderson added, much of agriculture’s geographic shift is tied directly to improvements in irrigation such as where rice is grown in China. “When we’re thinking about the future and future responses to climate change and the possibility of moving things out of these hotter regions,” Anderson explained, “it really remains intertwined with our ability to sustainably use water and to build irrigation infrastructure in a way that is conducive to growing these crops where we have the available land and nutrients.”

Vulnerable Beyond Climate

This past year’s East African floods may have boosted crop yields and eased food security concerns for people in rural areas, but the relief is temporary. “Climate impacts are triggers, not the main drivers” pushing smallholder farmers into poverty and insecurity, Ángel G. Muñoz said. Securing the world’s future food supply is as much about equity and economic stability as it is about sustainable agriculture, he said.

Consider, for example, factors driving the recent caravan of thousands of people from Central America, and Guatemala in particular, toward the United States. “What we have found…for the human migration that we saw in recent years from Guatemala is that it’s related to a multiyear drought that occurred between 2015 and 2017,” explained Muñoz, a climate scientist at IRI. Smallholder farmers on the brink of poverty faced year after year of poor harvest, lost income, and political instability that finally forced them to migrate northward in search of a way to support their families.

“What we have found is that, actually, although there is a clear climate signal,” he said, referring to the drought, “we do not see a

“IT NEEDS TO BE NATIONAL POLICY, BUT IMPLEMENTED LOCALLY, AND KEEPING VULNERABLE PEOPLE IN MIND SO THAT WE DON’T PUSH THEM TO THE EDGE.”

very important climate *change* signal in this particular migration.... Socioeconomic factors and understanding the local vulnerability of the population are far more important than actually thinking in terms of only one stressor,” such as climate change, driving farmers to new areas.

Not all countries or regions face the same socioeconomic problems as Guatemala, but that example highlights the need for climate-smart agricultural policies to consider vulnerabilities beyond climate and account for socioeconomic context. “That makes it a difficult problem to approach,” Anderson said, “because it’s certainly not something that can be solved entirely by scientists, or entirely through climate forecast-related approaches, or entirely in a policy sphere. You need all of these components, and so a lot of the work really is getting the right people talking to each other.”

The particulars of those components, Oniang’o said, greatly depend on the country, but each vulnerability makes any agricultural adaptation solution that much more difficult to accomplish. In many U.N.-designated developing economies, girls and women are severely undereducated and underrepresented in the workforce. In some countries, government corruption prevents monetary aid from reaching farmers in need. Most countries, however, are missing the mark at organizing a migration of agricultural areas and supporting the farmers needed to make it work, she said.

“Even when new policies come up, or new trade practices come up, or when the world order changes—even if it’s supposed to be in a positive way, it doesn’t affect smallholder farmers positively,” she said. “I see increasing vulnerability because we have not been able to address the poverty issue, low income, and hunger for many of the people I have been working with.”

“The people themselves say, ‘We have to move. We have to move from here.’ But someone must organize them to move,” Oniang’o added. “It needs to be national policy, but implemented locally, and keeping vulnerable people in mind so that we don’t push them to the edge.”

In the end, the paths leading toward a climate-smart global agriculture may already be well-worn by generations of farmers. “Indigenous communities in the north who rely on country foods that they harvest or hunt tend to be the most food-secure communities,” Turetsky said. “This is because these communities and traditions value the health of the boreal forest or the Arctic tundra. Any changes in local or commercial food production that do not uphold this value of the land or water may interfere with cultural traditions and practices. We must take the lessons learned from historical and existing food producing regions and ensure that we don’t repeat the same mistakes.”

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Boosting Weather Prediction with Machine Learning

Today predictions of the next several days' weather can be remarkably accurate, thanks to decades of development of equations that closely capture atmospheric processes. However, they are not perfect. Data-driven approaches that use machine learning and other artificial intelligence tools to learn from past weather patterns might provide even better forecasts, with lower computing costs.

Although progress has been made in developing machine learning approaches for weather forecasting, an easy method for comparing these approaches has been lacking. Now *Rasp et al.* present WeatherBench, a new data resource meant to serve as the first standard benchmark for making such comparisons. WeatherBench provides larger volume, diversity, and resolution of data than have been used in previous models.

These data are pulled from global weather estimates and observations captured over the past 40 years. The researchers have processed these data with an eye toward making them convenient for use in training, validating, and testing machine learning-based weather models. They have also proposed a standard metric for WeatherBench users to compare the accuracy of different models.

To encourage progress, the researchers challenge users of WeatherBench to accurately predict worldwide atmospheric pressure and temperature 3 and 5 days into the future—similar to tasks performed by traditional equation-based forecasting models. WeatherBench data, code, and guides are publicly available online.

The researchers hope that WeatherBench will foster competition, collaboration, and advances in the field and that it will enable other scientists to create data-driven approaches that can supplement traditional approaches while also using computing power more efficiently. (*Journal of Advances in Modeling Earth Systems (JAMES)*, https://doi.org/10.1029/2020MS002203, 2020) **—Sarah Stanley,** *Science Writer*

A Floating Buoy Fleet Could Help Scientists Track Rising Seas

Shane Elipot deploys an instrumented surface drifter from the NOAA research ship Ronald H. Brown *in 2012 in the North Atlantic Ocean. Credit: Molly Baringer, NOAA*

As climate warms, thermal expansion of seawater and meltwater from ice over land that flows into the ocean cause sea level rise, potentially threatening coastal communities and fragile coastal ecosystems. Rising sea levels therefore provide a way to measure climate change. Both local and global predictions of this rise rely on accurate sea level measurements.

Elipot proposes a new way to track sea level rise: a worldwide system of roving, satellite-tracked buoys. NOAA already maintains the Global Drifter Program, a fleet of freely drifting buoys, or surface drifters, that record ocean currents and other information, such as sea surface temperatures. These drifters are tracked by GPS to determine their 3D position on the surface of the ocean, but they transmit only their longitude and latitude to researchers, not their altitude, which could be used to estimate sea level, Elipot suggests.

To obtain meaningful regional and global sea level information, surface drifters would need to be equipped with standardized and relatively accurate GPS receivers. According to Elipot's simulations, an individual drifter's daily random vertical error of 1.6 meters would be accurate enough to lead to an error of only 0.3 millimeter per year for global mean sea level decadal trend estimates. As buoys in this program generally last less than a year, equipping new buoys to transmit altitude measurements as they are deployed would mean that the drifter fleet could begin reporting sea level data within a few years.

Global mean sea level is currently tracked using coastal tide gauges and satellite radar altimeters. The new research suggests that surface drifters would provide similar accuracy while extending the measurement range around the entire planet rather than only near coasts or within the limited latitudes covered by reference altimeter satellites. (*Geophysical Research Letters*, https://doi.org/10.1029/2020GL091078, 2020) **—Elizabeth Thompson,** *Science Writer*

Autonomous Minisubmarine Measures Seawater Conditions

Since the Industrial Revolution began in the mid-18th century, Earth's oceans have absorbed about one third of the carbon dioxide emitted through human activities. The ensuing roughly 30% increase in ocean acidity has reduced the amount of carbonate available for calcifying organisms such as corals and oysters to construct their skeletons and shells. As ocean acidity continues to climb, these biological structures could begin to dissolve or cost organisms extra energy to maintain, potentially disrupting marine food webs.

A Slocum glider operated by Rutgers University is deployed off the coast of New Jersey. Underwater gliders equipped with sensors provide live data that help scientists understand in real time how acidity is changing in Earth's oceans. Credit: Liza Wright-Fairbanks, Rutgers University

The rates at which the global ocean is acidifying are unprecedented, but the effects on coastal ecosystems, especially in economically important regions, are not well understood because of a lack of seasonal carbonate chemistry data. *Wright-Fairbanks et al.* report on an effort to help alleviate the data shortage using an underwater glider equipped with sensors to measure seasonal changes in ocean properties, including pH, temperature, dissolved oxygen, conductivity, and other parameters crucial to understanding local carbonate chemistry.

Between May 2018 and November 2019, the team deployed an autonomous Teledyne Webb Slocum G2 glider once per season, for a total of four missions, in the Mid-Atlantic Bight, the coastal region stretching from North Carolina to Massachusetts. The novel technology provided accurate, high-resolution measurements of seawater chemistry across the region.

The researchers detected the most acidic conditions in nearshore surface waters and cold bottom waters; the least acidic conditions occurred farther offshore, near the edge of the continental shelf, during fall and winter. The findings underscore the importance of seasonality, as well as biological activity and freshwater inputs, for controlling carbonate chemistry in the Mid-Atlantic Bight, the authors note. And they offer important baseline information for identifying drivers of ocean acidification—as well as strategies for fisheries management—in the Mid-Atlantic Bight, which hosts some of the United States' most economically important recreational and commercial fisheries as well as ecosystems crucial for protecting coastal communities during storms.

The study highlights the potential of autonomous technology for obtaining high-resolution records of marine carbonate chemistry data at a lower cost than traditional shipboard studies and in more extreme locales like polar regions or stormy seas, according to the researchers. They note that this technology could also be scaled up to help address national and even global requirements for improving the scientific understanding of ocean acidification. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2020JC016505, 2020) **—Terri Cook,** *Science Writer*

An Extraordinary Winter in the Polar North

The winter of 2019–2020 in the Northern Hemisphere was one of extremes. The massive region of cold polar air encircled by stratospheric winds, known as the stratospheric polar vortex, was particularly strong, keeping the frigid air whirling above the polar region and leading to a very mild winter in many regions farther south. The strong polar vortex coincided with a record-breaking positive Arctic Oscillation circulation pattern and record-low ozone levels in the Arctic that lasted into spring. In a review published as part of an AGU special collection on the 2019–2020 Arctic polar vortex, *Lawrence et al.* outline the unique conditions that allowed this "truly extraordinary" winter season to arise.

The researchers compared the unusual winter season with historical data and found that zonal (east-to-west) wind measures suggest that it was the strongest polar vortex since the satellite era began roughly 4 decades ago. The strength of the polar vortex varies from year to year and depends on many factors. Atmospheric waves originating in the troposphere often propagate into the stratosphere, breaking up and weakening the westerly circulation of the polar vortex.

But atmospheric wave activity was relatively weak last year. The authors suggest that the combination of this weak activity and multiple downward wave-coupling events, in which atmospheric waves propagating upward were reflected back into the troposphere, helped to cool and strengthen the polar vortex. These stratospheric wave reflection events and the persistently strong polar vortex likely helped to maintain the positive Arctic Oscillation, which in turn contributed to record warmth in places like Siberia. The strong and stable polar vortex was also conducive to the chemical destruction of ozone, the authors note. Ozone levels reached lows never before seen in the springtime in the Arctic.

The team identified several potential directions for future research on the exceptionally strong polar vortex and its links to other record-breaking phenomena. Among others, these directions include looking in more detail at the specific drivers of the events and how they relate to internal climate variability and studying downstream impacts of the events. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2020JD033271, 2020) **—Kate Wheeling,** *Science Writer*

Tracking Trace Elements in the Ganga River

The Ganga (Ganges) River, which flows through northern India and Bangladesh, drains more than 1 million square kilometers of land and provides water to almost half a billion people along its course from the Himalayas to the Bay of Bengal. The river is an immensely important socioeconomic and ecological feature in the region, but it is also intensely polluted. Local agencies collect data about the river, but scientists still lack a clear understanding of how dissolved trace and heavy metals vary along its course.

Both trace and heavy metals can be toxic to humans. Heavy metals, such as chromium, arsenic, and lead, especially can cause severe illnesses at even low concentrations. To create a more comprehensive picture of how concentrations of these metals change across the river's geography and to provide a baseline for future studies, *Boral et al.* analyzed 243 different water samples for 15 trace elements. The samples came from 38 sites in the Indian portion of the Ganga Basin and were collected between 2014 and 2016 in every stage of the monsoon season (before, during, and after).

By combining these data with time series samples taken from the farthest downstream point studied, at the town of Manikchak, the scientists tracked where these dissolved metals were entering the river and how they were being diluted along the way. They found that trace and heavy metal concentrations in the Ganga River varied considerably with geography. Near the river's source, Himalayan glaciers contribute to higher levels of dissolved trace elements, which the researchers attributed to freshly eroded and reactive rock fragments (known as glacial flour) that enter the river as glaciers erode bedrock.

Downstream, where urban and industrial centers are more prevalent amid the river's floodplains, the scientists observed large spikes in trace elements in river water. However, as large tributaries join the river, trace element concentrations drop quickly, leading the researchers to conclude that dissolved metal pollution is not widespread in the river but, rather, is linked to pollution hot spots.

Overall, the work shows that current trace element pollution in the Ganga River is not significantly higher than the global average for rivers and is lower than previous estimates have suggested. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2020GC009203, 2020) **—David Shultz,** *Science Writer*

The Alaknanda River, seen here near Chamoli district in Uttarakhand, India, combines with the Bhagirathi River to form what is thereafter called the Ganga River. Credit: Soumita Boral

Gravity Waves Leave Ripples Across a Glowing Night Sky

Waves propelled through the air by distant thunderstorms produced glowing bands in the sky during a 2016 "bright night" event, when the atmosphere was illuminated by a green glow visible to the naked eye. The ripples disturbed an atmospheric layer nearly 90 kilometers (56 miles) above the El Leoncito Astronomical Complex in Argentina, at an altitude where reactions between oxygen molecules produce the brilliant airglow of a bright night; solar energy hitting Earth's magnetic field excites the same molecules to create aurorae. The new observations suggest that gravity waves from storms have bigger impacts on global and space weather than expected.

During a bright night event in 2016, gravity waves produced by a distant thunderstorm left ripples in the glowing atmosphere, as seen from Las Campanas Observatory in Chile. Credit: AGU/Yuri Beletsky/Las Campanas Observatory

The energy and momentum transported by these thunderstorms were much greater than expected, according to *Smith et al.*

Gravity waves occur in a variety of ways, from the wind producing waves on an ocean surface to storms producing atmospheric waves that ripple through the air. Atmospheric gravity waves can affect weather by reorienting wind and producing air turbulence.

Although there have been previous observations of gravity waves affecting airglow at such high altitudes, the newly described event was remarkable for its brightness and persistence. By combining satellite imagery and data captured by an all-sky imager, the researchers determined that the gravity wave ripples originated from a thunderstorm complex several hundred kilometers away. These measurements also enabled the calculation of the wave's momentum flux, or how much "push" it had, which was several times larger than previously observed.

The authors said that this will have an impact on how scientists model the effect of gravity waves for both global wind circulation and radio wave propagation through the ionosphere. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2020JD033381, 2020) **—Jack Lee,** *Science Writer*

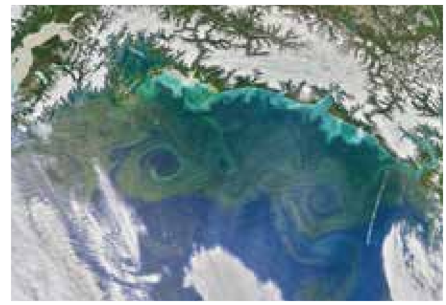
A Promising Development for Detecting Ocean Productivity

The ocean's primary productivity—the pace at which organisms photosynthesize organic compounds—is an integral part of the global carbon cycle, which affects the cycling of important nutrients and trace metals in marine ecosystems. Ocean primary productivity also controls carbon dioxide exchange between the air and the sea, which in turn affects the concentration of this gas in Earth's atmosphere.

Despite the fundamental importance of primary productivity, direct measurements of the process remain difficult to obtain, in part because disposal of the radioisotopes required for the traditional bottle incubation method is difficult and expensive. The resulting lack of information has left oceanographers unable to accurately determine how ocean primary productivity patterns vary through space and time.

To help fill this gap, *Henderikx Freitas et al.* tested the potential of both ship- and float-based platforms to estimate ocean primary productivity during a 2017 research cruise from Alaska to Hawaii. During the transit, which crossed almost 40 degrees of latitude, the team made frequent in situ observations of carbon and oxygen concentrations via three different methods to estimate production and respiration rates across this ecologically diverse swath of the North Pacific.

The float and shipboard measurements yielded similar estimates, a finding that suggests that autonomous, float-based platforms have the potential to greatly expand our knowledge of global ocean productivity patterns. The researchers also observed that the marine ecosystem's metabolic characteristics were consistent along the transect, a surprising result given the large-scale transition from nutrient-rich subpolar waters to nutrient-depleted subtropical conditions and the corresponding tenfold decrease in biomass.



A large plankton bloom, fed by nutrients in glacial runoff and mixed by eddies, is seen in the Gulf of Alaska in this image taken in June 2016. Credit: NASA image by Norman Kuring

According to the authors, the study results offer a potential path forward for obtaining data needed to constrain spatial and temporal trends in ocean primary productivity and to establish a basis for evaluating model- and satellite-based estimates, which currently have large uncertainties. If further testing supports the paper's conclusions, oceanographers will have a practical technique with which to elucidate long-term ecological consequences of global warming on the marine food web. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2019GB006518, 2020) **—Terri Cook,** *Science Writer*

A Precise Mosaic View of Mars's South Pole

To get a precise view of a planet's surface, scientists can build a mosaic using images captured by cameras mounted on an orbiting spacecraft. This process requires accounting for how the spacecraft and its camera were oriented when each photo was taken, as well as how that positioning corresponds to existing topographic data. Software speeds the task, but the process typically still demands a lot of manual work.

Layers of Mars's south polar cap, composed mainly of frozen carbon dioxide, are visible in this image cropped from a new mosaic of the planet's southern polar region. Researchers have designed a new procedure for building such mosaics of a planetary surface from spacecraft images. Credit: NASA/JPL/Malin Space Science Systems/Southwest Research Institute

Now *Robbins et al.* have developed a workflow that automates many of the manual steps of the mosaic-building process. The novel approach eases the key challenge of accurately tying specific features, such as the rim of a crater, together in different images, minimizing the chance that small errors will accumulate.

To demonstrate the value of the new workflow, the researchers applied it to the Martian south pole and its surroundings. They selected this region because its dust storms, heavy frost, other harsh weather, and difficult lighting conditions make it particularly challenging to build an accurate mosaic with manual corrections.

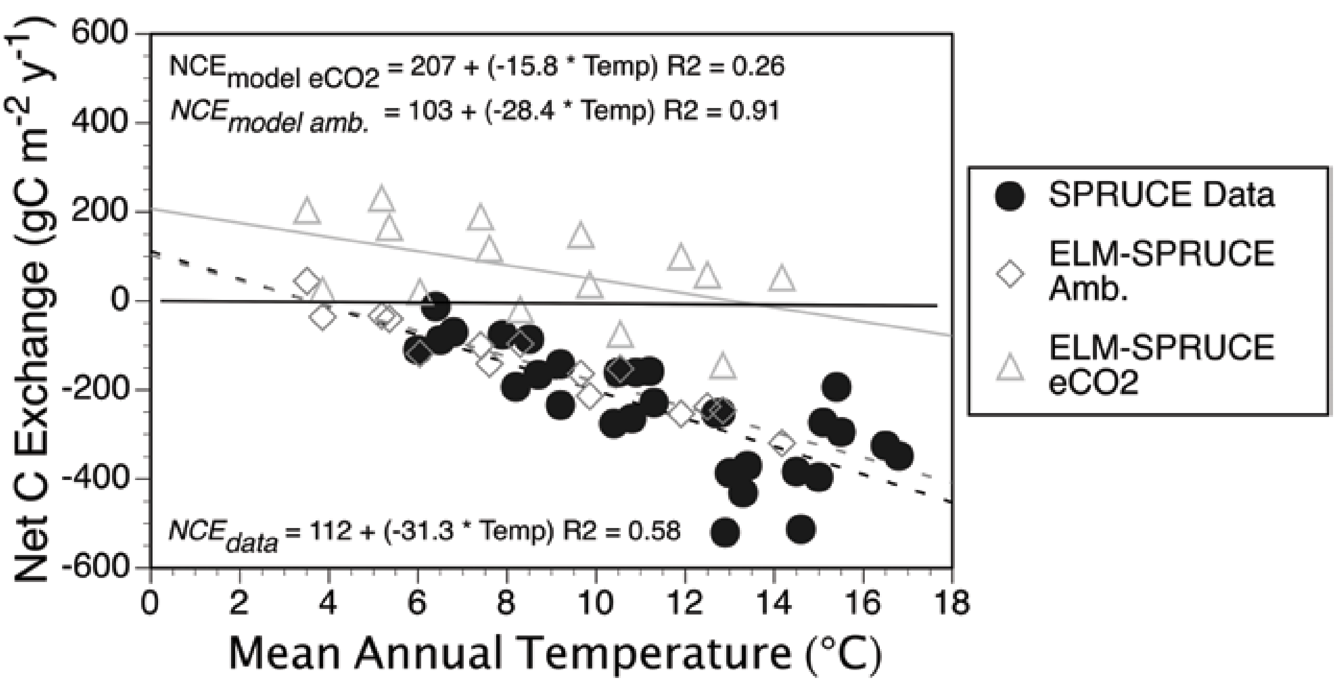
The new workflow successfully generated a mosaic of the south polar region from 9,652 images captured by the Context Camera aboard the Mars Reconnaissance Orbiter and tied to topographic data collected by the Mars Orbiter Laser Altimeter. The mosaic comprises 255 billion pixels, with each pixel representing 6 meters of Martian ground, and is significantly more accurate than earlier mosaics of the same region.

The researchers have made the new mosaic and its underlying data publicly available as a resource for future Mars research through NASA's Planetary Data System Cartography and Imaging Sciences Node Annex. Meanwhile, ongoing efforts by the authors and other researchers could apply the new workflow to create mosaics for other regions on Mars—or for other planetary bodies. (*Earth and Space Science*, https://doi.org/10.1029/2019EA001054, 2020) **—Sarah Stanley,** *Science Writer*

Balanced Rocks Help Measure Earthquake Risk

Earthquake hazard calculations are uncertain because we cannot go back in time to verify large but infrequent seismic events. Therefore, scientists expect a range of shaking that is inferred from earthquake rates of nearby faults. To narrow that range, *Rood et al.* homed in on precariously balanced rocks located along California's central coast. They used innovative age dating methods to determine that some of these rocks had been in place for at least 20,000 years, and they modeled the forces necessary to topple them. With that information, it is possible to exclude the possibility of some of the more frequent and greatest shaking outcomes from the suite of possibilities. The authors find that their analysis reduces the uncertainty in regional seismic hazard calculations by 49%. (https://doi.org/10.1029/2020AV000182, 2020) **—Tom Parsons**

Unexpected Bog Response Offers New Insights



Measured changes in net carbon exchange (solid circles) in a Minnesota bog showed increasing carbon losses (larger negative values) as temperature was experimentally increased. The ELM-SPRUCE model simulated this loss well under ambient carbon dioxide (CO_2) conditions (open diamonds and dashed gray line), but the same model for elevated CO_2 predicted carbon gains that did not occur (open triangles and solid gray line). Credit: Hanson et al., 2020

Boreal peatlands store large stocks of soil carbon that are subject to decomposition as the region undergoes above-average warming compared with the global mean. *Hanson et al.* used novel technologies to warm both aboveground and belowground parts of the ecosystem at a northern Minnesota bog, with and without elevated carbon dioxide (CO_2). Not surprisingly, carbon was lost with warming. But contrary to model predictions, the elevated CO_2 treatment had only minor effects. We learn new insights when models fail. In this case, it appears that the dominant plants of these northern Minnesota bogs do not respond significantly to CO_2 enhancement, as most plant models predict. Revised models for this important biome now need to be tested at other sites to improve our understanding of the likely carbon losses that could contribute to accelerating climate change. (https://doi.org/10.1029/2020AV000163, 2020) **—Eric A. Davidson**

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Greetings from the sea ice just offshore Utqiagvik (formerly Barrow), Alaska!

In this photo, taken in early March 2020, Radford University student researcher Deanna Perales (left) is getting ready to drill into the ice so she can lower her self-made, high-sensitivity water pressure sensor into the Chukchi Sea. Her Arduino-controlled sensor will record pressure variations in the seawater (at a rate of 1 hertz) to check for correlations between those changes and ice cracking as recorded by another student's self-made seismic detectors. Her work partner and fellow student Will Nape is steadying the ice corer as she gets ready to start.

The day was gray and threatening, with a storm front looming in the distance behind Deanna. She quickly got her sensor into the water and collected nearly an hour of data that day before a blizzard chased us off the ice. We are currently analyzing these and other data to see how tiny ocean pressure changes may correlate with the formation of the ubiquitous ice fissures.

With the experience she gained on this trip, Deanna plans to return to the ice in 2022 with her own improved design and with the goal of recording data over the course of many days. This work is part of the yearlong Arctic Geophysics Research Experience classes, in which students design their own experimental questions, build their own sensors to address those questions, and then deploy their work on the Arctic sea ice.

—**Rhett Herman,** Radford University, Radford, Va.

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