

An underwater photograph featuring a large sea turtle in the foreground, swimming towards the left. The turtle's head and front flipper are prominent, showing detailed patterns on its shell. Behind it, a school of silver fish swims in the same direction. The background shows a sandy ocean floor with some rocks and coral under clear blue water.

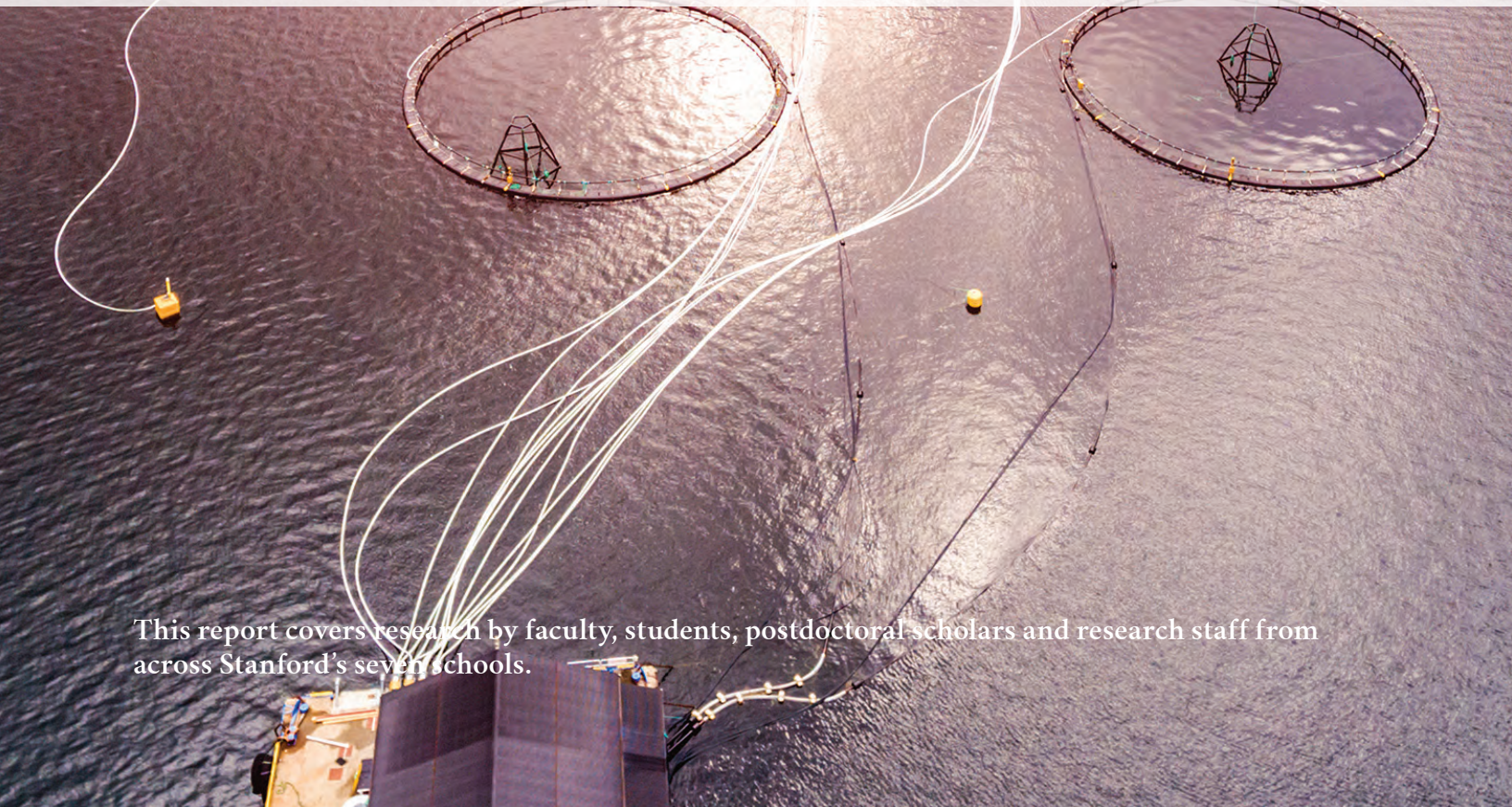
STANFORD

ENVIRONMENTAL RESEARCH

2021 YEAR IN REVIEW



Stanford
WOODS
INSTITUTE *for the*
ENVIRONMENT



This report covers research by faculty, students, postdoctoral scholars and research staff from across Stanford's seven schools.

DIRECTOR'S NOTE

With a continuing global pandemic and impacts from a changing climate disrupting the daily lives of millions of people worldwide, Stanford researchers have extended the frontiers, developing new tools, discovering new phenomena, and better understanding risks to improve the lives of people and the environment.

Managing conservation and biodiversity while also protecting human health and food security is a tremendous challenge, made all the more difficult with ongoing changes in the global climate. With the Blue Food Assessment, two major programs at Stanford, the Center for Ocean Solutions and the Center on Food Security and the Environment, have come together to offer a stunning array of recommendations and findings that forward aquatic foods as a climate, food, and ocean solution. Researchers working at the nexus of public health and ecology have shown that improving biodiversity can also prevent disease spillover events from wildlife to humans, likely the cause of the COVID-19 pandemic. By working across disciplines, these teams are able to offer innovative ideas to solve pressing, important problems.

Researchers across many disciplines have developed innovations and analysis on desalination, carbon storage, sea-level rise adaptation, methane removal and more. Highlighting the connections between societal concerns and environmental realities, Stanford scholars showed the relationships between piped water and gender equality, government oversight and air quality, and extreme events and weather prediction.

The Stanford Woods Institute for the Environment is the interdisciplinary hub of environmental research and solutions at Stanford. I am very excited to share with you this collection of environmental research, which shows the breadth and potential of the university's commitment to scholarship on sustainability. This work celebrates Stanford researchers' deep expertise in their research areas as well as the incredible impact of their work in an interdisciplinary solutions space. We look forward to seeing this excellence grow and expand in the coming year as we join the new school focused on climate and sustainability.

As we celebrate Stanford's increasing commitment and focus on the environment and sustainability, the Woods community will continue to lead the way towards bridging research and impact.



Christopher Field

Christopher Field
Perry L. McCarty Director



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RESEARCH AWARDS FOR ENVIRONMENTAL SOLUTIONS

In order to tackle immense environmental challenges, scientists, engineers, law experts, social scientists, and other scholars must take risks and enact bold, creative research plans. In 2021, the Stanford Woods Institute for the Environment awarded more than \$1.5 million to 10 innovative projects in the form of Environmental Venture Projects (EVP) and Realizing Environmental Innovation Program (REIP) grants. These programs support interdisciplinary research projects with up to \$200,000 per project geared towards solving major environmental problems.

Since EVP began in 2004 and REIP began in 2015, the Stanford Woods Institute has awarded more than \$19 million in grants to 122 research teams representing all of Stanford's seven schools with work in 33 different countries. These projects have gone on to receive more than \$47 million in additional funding from other sources.

ENVIRONMENTAL VENTURE PROJECTS

The goal of EVP grants is to support interdisciplinary, high-risk research projects that identify and develop real-world solutions. The projects selected for 2021 will receive up to \$200,000 over two years:

Improving plastic waste management: Every year, 359 million tons of plastic waste are generated and about 150-200 million tons accumulate in the natural environment. Single-use plastic waste will likely persist for thousands if not millions of years. To address the way plastic waste is processed, this project will engineer highly active enzymes and microbes capable of breaking down polyesters in a decentralized network of “living” waste receptacles. Additionally, the researchers are building a quantitative model of plastic recycling behaviors, are in dialogue with leading apparel companies, and exploring options for a start-up venture to scale and bring the technology to market for consumer adoption. Jennifer Cochran (Bioengineering), Craig Criddle (Civil and Environmental Engineering) and Erin MacDonald (Mechanical Engineering)

Protecting women’s health: Metal exposure during pregnancy has been associated with adverse birth outcomes, yet the link between metals and stillbirth risk remains unclear. This project aims to identify sources of metal exposure among pregnant women in Bangladesh, and how this exposure may contribute to the elevated rate of stillbirth. The researchers will leverage the framework of an ongoing child health surveillance study to compare placental biomarkers of metal exposure among stillbirths and live births. The team will look at concentrations of various metals in drinking water, soil, rice, and turmeric to identify the routes of exposure. This will inform interventions to reduce pregnant women’s exposure to metals and may show how environmental metals are connected to stillbirth. Stephen Luby (Medicine), Gary Shaw (Pediatrics) and Scott Fendorf (Earth System Science)

Tracking and treating viruses in water: Research on human viruses is relatively void of data on virus persistence in the environment. This project aims to carry out novel research on virus persistence in water, focusing on two important groups of viruses: human norovirus (HNoV) and human coronaviruses (HCoVs). The researchers will study the persistence of infectious HNoV in water, the persistence of CoVs, including SARS-CoV-2, in water and wastewater, and the potential for disinfection by free chlorine. Results from these studies will have immediate applications to inform wastewater reuse and recreational water quality standards. Alexandria Boehm (Civil and Environmental Engineering), Catherine Blish (Microbiology and Immunology), Harry

Greenberg (Microbiology and Immunology) and William Mitch (Civil and Environmental Engineering)

Improving climate change messaging: Approaches to climate change communication that increase belief in and/or concern about the phenomenon suffer from lack of organization, incommensurable measures and sampled populations, and very underpowered empirical tests. This project will create a large-scale experimental tournament of 12 promising climate change messaging approaches. The researchers will test the effects of each on belief in, and concern about climate change in comparison to one another and to a placebo control. Rob Willer (Sociology), Neil Malhotra (GSB) and Jane Kathryn Willenbring (Geological Sciences)

Monitoring gas pollution in the Arctic: Gas sensing in remote regions and in our oceans is becoming increasingly important for developing global warming mitigation strategies. This project will develop a monitoring strategy with inexpensive, passive and biodegradable sensors combined with optical spectroscopy. The sensors are placed in corner-cube arrays that acts as retroreflectors, whose signals are remotely detected by spectroscopic interrogators that can be placed in stationary base stations or on movable platforms, such as airplanes and drones. The research has a dual focus of developing the sensor technology and the deployment strategy. Olav Solgaard (Electrical Engineering) and David Reis (Applied Physics)

Measuring soil moisture from space: Present methods of measuring water content remotely are very coarse, mostly at tens of kilometers resolution, and therefore, do not satisfy the needs of the agricultural industry. This project will develop a new method of analyzing spaceborne radar data at 10m resolution to meet this added need. Using satellite data, the researchers will test a new processing and analysis approach to yield estimates of soil moisture at finer resolution than is currently possible with remote methods. This method, if successful, could be a powerful new tool for cropland management. Howard Zebker (Geophysics and Electrical Engineering) and Alexandra Konings (Earth System Science)

REALIZING ENVIRONMENTAL INNOVATION PROGRAM

REIP grants are intended to move projects from the discovery phase of research to the validation phase and ultimately, to widespread adoption. The projects selected for 2021 will receive up to \$200,000 over two years:

Sustaining the Upper Colorado River: Colorado River basin water law reserved no water for riverine ecosystems and today, the basin's rivers routinely run so low that severe ecological damage to fish habitat occurs. Buying water to protect ecosystems through private water rights transactions — a proven market mechanism to restore river flows — entails conservation buyers pursuing individual water sellers on a mostly ad hoc basis instead of a cost-effective regional strategy. This project aims to deploy a novel ecohydrologic-economic-legal model that optimizes ecological preservation, identifies the most beneficial set of surface-water market transactions for ecosystems in the Upper Colorado River basin, and informs water-rights markets to help conservation organizations maximize fish habitat restoration cost effectively. Steven Gorelick (Earth System Science) and Barton “Buzz” Thompson (Law)

Combatting the illegal wildlife trade: The illegal wildlife trade (IWT) is at least a \$23 billion per year industry that is greatly reducing biodiversity, degrading ecosystem functions, threatening the world with emerging infectious diseases, and is closely linked to human trafficking, regional destabilization and terrorism. A key limitation in the fight against IWT is an inability to identify where animal materials are coming from and distinguish between legal and illegal products. Leveraging genomics technology, new collaborations and existing research, this project will develop a tool to identify the geographic origin of confiscated materials inexpensively and in-country. The researchers will focus on African lions in partnership with government agencies and NGOs and the information will be used to identify and disrupt trafficking routes, strengthen law enforcement, and implement community engagement responses. Dmitri Petrov (Biology) and David Relman (Microbiology and Immunology)

Empowering small-scale fishers: Fisheries supply chains are becoming increasingly digitized, creating faster and more reliable avenues of market access for small-scale fishers. However, it is not yet understood if these technologies improve fishers' livelihoods and influence fishers' decision-making (e.g., evaluation of environmental impacts). This project will deploy a well-established digital platform by ABALOBI with fishers in the Republic of Palau. Using a quasi-experimental design, the researchers will track socioeconomic and decision-making metrics before, during, and after deployment of the ABALOBI app, generating actionable and scalable insights into the role of technological interventions in empowering small-scale fishers and promoting sustainable solutions for fishing communities. Gabrielle Wong-Parodi (Earth System Science), Michael Bernstein (Computer Science) and Fiorenza Micheli (Biology)

Making cities healthier: In cities today, urbanization reduces experience of nature, sedentary, nature-deprived urban lifestyles increase health burdens and risks, and highly uneven access to nature exacerbates multiple inequalities. Revealing where and how nature provides greatest benefits to people can inform and motivate investments in urban design with nature. This project will integrate a wealth of new data, science and analytics as well as deep relationships with urban leaders and networks. By developing actionable science and demonstrating the findings for San Francisco, Guangzhou and Singapore, this project will inform urban planning and policy, enhance urban nature, and improve health, equity, livability, and sustainability. Gretchen Daily (Biology), Abby King (Epidemiology and Public Health) and Kari Nadeau (Pediatrics and Medicine)

Investing in Methane Removal

Removing roughly three years-worth of methane emissions would reduce global surface temperatures by approximately 0.21°C while reducing ozone levels enough to prevent about 50,000 premature deaths annually, according to two Stanford-led studies published in *Philosophical Transactions of the Royal Society A*. The studies, which received funding from an EVP grant, could help shape climate policy to value methane removal closer to carbon dioxide removal, which has received significantly more research and investment.

Methane is 81 times more potent in terms of climate warming over the first 20 years after its release, and about 27 times more potent over a century. Methane reduction can also improve air quality by decreasing concentration of tropospheric ozone, which causes respiratory illnesses and an estimated one million premature deaths globally each year.

The modeling study examines methane removal's potential impacts while accounting for its shorter lifetime than carbon dioxide. The researchers found that under a high emissions scenario, a 40% reduction in global methane emissions by 2050 would lead to a temperature reduction of approximately 0.4°C by 2050. In a low emissions scenario, the same methane removal could reduce the peak temperature by up to 1 degree Celsius.

The research agenda paper compares and contrasts aspects of carbon dioxide and methane removal, describes methane removal technologies and outlines a framework for accelerating scale-up.



The time is ripe to invest in methane removal technologies. Carbon dioxide removal has received billions of dollars of investments, with dozens of companies formed. We need similar commitments for methane removal.

— Rob Jackson, professor of Earth System Science



Abernethy, S., O'Connor, F. M., Jones, C. D., & Jackson, R. B. (2021). Methane removal and the proportional reductions in surface temperature and ozone. *Philosophical Transactions of the Royal Society A*, 379(2210).

Jackson, R. B., Abernethy, S., Canadell, J. G., Cargnello, M., Davis, S. J., Féron, S., Fuss, S., Heyer, A. J., Hong, C., Jones, C. D., Damon Matthews, H., O'Connor, F. M., Pisciotta, M., Rhoda, H. M., De Richter, R., Solomon, E. I., Wilcox, J. L., & Zickfeld, K. (2021). Atmospheric methane removal: a research agenda. *Philosophical Transactions of the Royal Society A*, 379(2210).



Dan Brekke



Clean Air Task Force



Biodiversity and Prevention of Spillover

Identifying solutions that preserve and restore biodiversity while also protecting human health are critical for both people and the environment. The COVID-19 pandemic highlighted the threat of zoonotic spillover, where pathogens from wild animals can spark epidemics and pandemics in humans and livestock. In a Stanford-led study, published in *Current Biology*, researchers review the scientific literature to better understand how biodiversity conservation can help reduce the risk of zoonotic spillover.

Encompassing multiple aspects of biodiversity, the study, which received funding from an EVP grant, identifies cases where zoonotic pathogen spillover is mechanistically linked to changes in biodiversity and describes general principles that can guide future research.

One generality is that large, intact habitat reduces overlap among host species and reduces contact between humans and wildlife, making a spillover opportunity less likely while promoting wildlife health. Further, the loss of predators and competitors can reduce regulation of host and vector populations, such as rodents that may carry disease. In this case, less biodiversity would mean more of a species that could carry pathogens to humans.

“The world is undergoing rapid anthropogenic change with detrimental effects on biodiversity and the health of organisms, including humans. Efforts are underway to combat the impact of anthropogenic disturbances on biodiversity,” wrote the authors. “However, since biodiversity change may affect zoonotic disease spillover through multiple mechanisms, it is imperative that

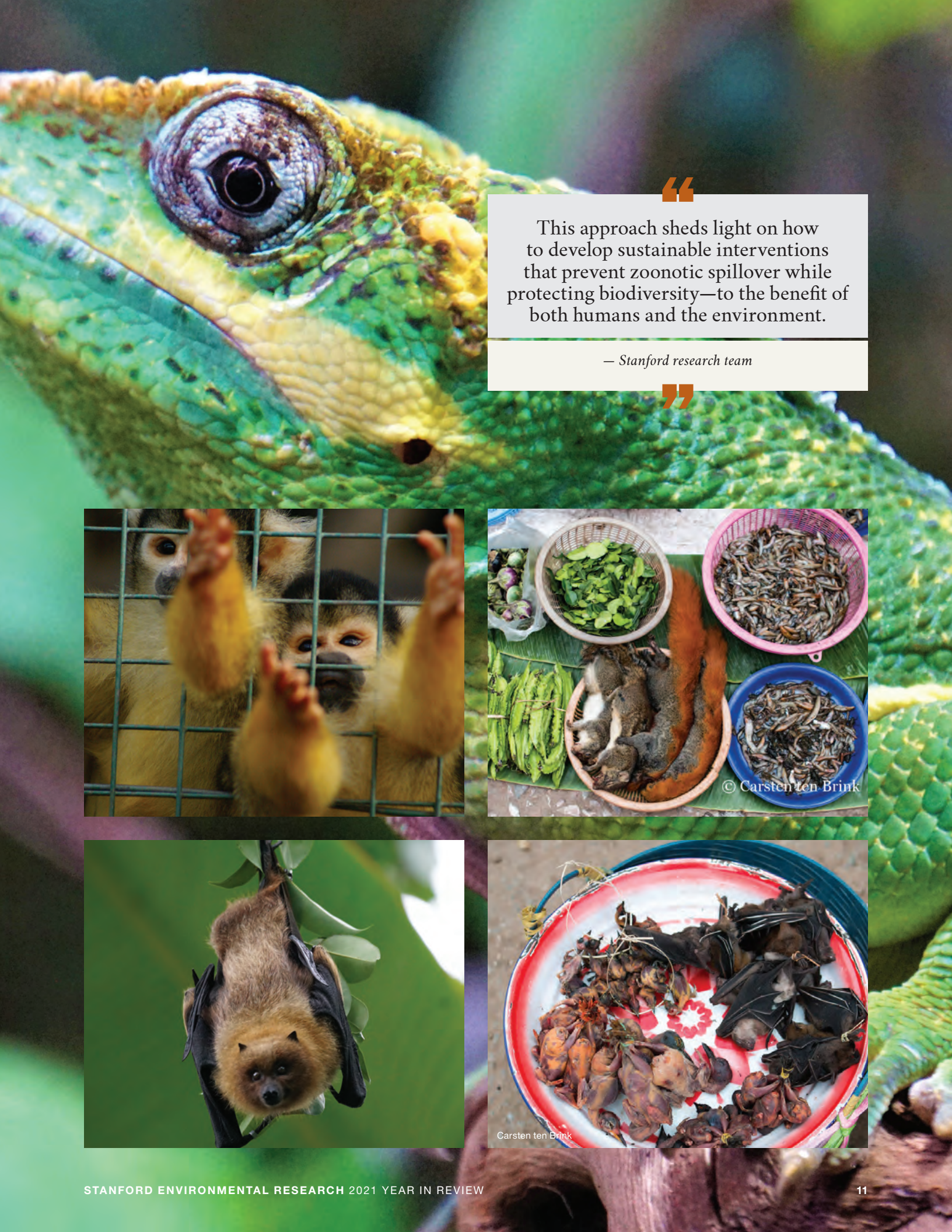
biodiversity conservation efforts also incorporate actions to prevent spillover.”

Moreover, species that carry pathogens are better adapted to human-dominated landscapes and managing invasive reservoir hosts and vectors would be useful in preventing spillover events. Human activities such as the commercial wildlife trade, transportation of livestock and pets, and introduction of invasive species introduce more opportunities for spillover events to occur. Efforts to fight the illegal wildlife trade should also include efforts to prevent spillover events, argue the researchers.

This work also involved an interdisciplinary research team at Stanford led by lead author Caroline Glidden, postdoctoral scholar in Biology, and senior author Erin Mordecai, professor of Biology.

Glidden, C. K., Nova, N., Kain, M. P., Lagerstrom, K. M., Skinner, E. B., Mandel, L., Sokolow, S. H., Plowright, R. K., Dirzo, R., De Leo, G. A., & Mordecai, E. A. (2021). Human-mediated impacts on biodiversity and the consequences for zoonotic disease spillover. *Current Biology*, 31(19), R1342–R1361.





This approach sheds light on how to develop sustainable interventions that prevent zoonotic spillover while protecting biodiversity—to the benefit of both humans and the environment.

— Stanford research team





RESEARCH HIGHLIGHTS



Lowering the High Cost of Desalination

Desalination, the process of removing salt and impurities from sea-, ground- and wastewater, has the potential to solve global freshwater crises. While plants do exist on coasts next to seawater, making salty impure water drinkable is more difficult for inland water sources, which can have up to 10 times higher concentration of dissolved solids than seawater, because disposing of concentrated brine, the waste stream from desalination, is very expensive.

“When we desalinate water, we are left with a pure water stream and a concentrated waste stream. Inland brackish water and wastewater desalination plants are costly to build and to operate because we don’t have easy disposal options for the concentrate stream,” said Meagan Mauter, associate professor of Civil and Environmental Engineering.

In a paper in the *Proceedings of the National Academy of Sciences*, Mauter introduces a suite of new analytic methods that could help desalination engineers weigh technical and financial factors that go into building a desalination plant.

This “innovation assessment model” is applied to analyze membrane-based desalination where impure water is separated from freshwater by a permeable material with pores big enough for water molecules to flow through, but small enough to stop salt and other solid impurities. High-salinity membrane separation processes can involve hundreds of interdependent components or design variables which impact efficacy and cost. Mauter’s approach allows engineers to test innovative ideas before they build prototypes which can lower the cost of desalination.

Dudchenko, A. V., Bartholomew, T. V., & Mauter, M. S. (2021). High-impact innovations for high-salinity membrane desalination. *Proceedings of the National Academy of Sciences of the United States of America*, 118(37), 2022196118.



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Innovation is not always intuitive. Often, the cost increases of these new technologies negate any performance improvements. Our method helps prioritize the research and development pipeline and helps to earmark scarce research dollars for innovations with the greatest potential benefit.

— Meagan Mauter, associate professor
of Civil and Environmental Engineering

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Waleed Alzuhair



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Felix Clay/Duckrabbit

Piped Water and Equity

Roughly 844 million people across the globe live without safe, accessible water for drinking, cooking, cleaning, hygiene and food production. Just 12% of the rural population in sub-Saharan Africa has water piped to their home. Other families collect water from distant sources with women and girls overwhelmingly responsible for carrying 40-pound containers, which takes time away from childcare, hygiene, outside employment, education and other activities.

A Stanford study published in *Social Science & Medicine* shows how bringing piped water closer to remote households in Zambia dramatically improves the lives of women and girls, promotes gender equality and improves well-being. The work can inform governments and NGOs evaluating the costs and benefits of piped water as an alternative to less accessible communal water sources.

“Switching from the village borehole to piped supply saved almost 200 hours of fetching time per year for a typical household,” said study senior author Jenna Davis, professor of Civil and Environmental Engineering and director of Stanford’s Program on Water, Health and Development.

The researchers studied four similar rural villages in Zambia. Halfway through, two of the villages received piped water to their yard, which reduced their distance to water to just 15 meters. The researchers found households with piped water spent 80% less time fetching water, saving close to four hours a week mostly for women and girls. The time saved was spent gardening, performing chores, caring for children or working. These families also reported being happier, healthier and less worried.

Winter, J. C., Darmstadt, G. L., & Davis, J. (2021). The role of piped water supplies in advancing health, economic development, and gender equality in rural communities. *Social Science & Medicine*, 270, 113599.



Addressing this problem provides the time and water for women and girls to invest in their household’s health and economic development, in whatever way they see fit.

— James Winter, a Ph.D. candidate in Civil and Environmental Engineering



Rohit Ramchandani



Clayton Smith

Illuminating a Sea Turtle Mystery

The North Pacific loggerhead turtles' years-long epic migration between their birthplace on Japan's beaches and reemergence near the coast of Baja California has been a longstanding mystery. These turtles are endangered but because little is known about their movement between disparate locations, it is difficult to effectively assess and protect them.

"Understanding how and why species like the North Pacific loggerhead move among habitats is crucial to helping them navigate threats," said study senior author Larry Crowder, professor at Stanford's Hopkins Marine Station.

Through compiling data from satellite tracking and other techniques and collecting detailed records of sea turtle aging and stable isotope testing, Stanford researchers and others have revealed a unique phenomenon that may explain the turtles' pathway.

The research, published in *Frontiers in Marine Science*, shows evidence for how some sea turtles — creatures highly sensitive to temperature — can cross a frigid zone called the Eastern Pacific Barrier that normally stops most creatures. Intermittent passages of warm water allows sea turtles to cross cold ocean barriers that would be otherwise inhospitable. The results could inform design of conservation measures to protect sea turtles and other migratory sea species amid changes in climate that are altering their movements.

"This work builds on the backbone of exceptional research about these 'lost years,' and for the first time ever we are excited to provide evidence of a 'thermal corridor' to explain a longstanding mystery of one of the ocean's greatest migrants" said study lead author Dana Briscoe, who was a research associate at the Stanford Woods Institute for the Environment during the research and now works at the Cawthron Institute.

Briscoe, D. K., Turner Tomaszewicz, C. N., Seminoff, J. A., Parker, D. M., Balazs, G. H., Polovina, J. J., Kurita, M., Okamoto, H., Saito, T., Rice, M. R., & Crowder, L. B. (2021). Dynamic Thermal Corridor May Connect Endangered Loggerhead Sea Turtles Across the Pacific Ocean. *Frontiers in Marine Science*, 8, 185.

For decades, our ability to connect the migratory dots for this endangered species has remained elusive.

— Dana Briscoe, research associate at the Stanford Woods Institute for the Environment





Changing Risk and Burden of U.S. Wildfires

In recent years, wildfires have accounted for up to half of the fine particle pollution PM2.5 in areas of the American West. Smoke from wildfires is becoming a widely felt health impact of climate change. In a perspective in the *Proceedings of the National Academy of Sciences*, Stanford experts detailed the causes and impacts of the rapid acceleration of wildfires.

Homes at risk from wildfires are on the rise with 50 million now sitting in the country's wildland-urban interface next to combustible vegetation. Yet, being close to fires is no longer necessary to feel their effects — the researchers estimated about 25% of the PM2.5 nationwide is attributable to wildfires.

“Climate change is a primary driver of these changes, and this particular climate impact is one we need to pay a lot more attention to,” said Marshall Burke, associate professor of Earth System Science.

The researchers warn that U.S. clean air regulations are not prepared to deal with the new and worsening wildfire reality. Wildfires are not regulated under the Clean Air Act and their smoke is not a federal air quality violation.

“Under current law, wildfire smoke is classified as an “exceptional event” that is essentially uncontrollable and so not subject to traditional air pollution control law. The reality is that wildfire is very much a managed outcome, but not in the same sense that a smokestack emitting air pollutants is,” said Michael Wara, director of the Woods

Institute's Climate and Energy Policy Program. “Resolving this dilemma is a key challenge for forest managers and air pollution regulators.”

The researchers stress that more research is needed to understand the impacts of acute and chronic exposure to wildfire smoke on human health.

Burke, M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., & Wara, M. (2021). The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, 118(2).

Jeff Hall/CALFIRE



Bob Dass





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How these extremely elevated ambient concentrations of hazardous air pollutants translate to exposures and health outcomes in the context of the U.S. is an area of developing scienc.

— *Michael Wara, director of the Woods Institute's Climate and Energy Policy Program*

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Mike DeRusha/USACE



Solving the Mystery of Supercell Storms' Icy Plumes

A cloudy plume of ice and water vapor billowing up above the top of a severe thunderstorm often precedes a devastating tornado, high winds or large hailstones. They can be spotted in satellite imagery, often occurring 30 minutes or more before severe weather reaches the ground.

“The question is, why is this plume associated with the worst conditions, and how does it exist in the first place?” said Morgan O’Neill, assistant professor of Earth System Science and lead author of the study, published in *Science*, which revealed the mechanism for these plumes could be tied to “hydraulic jumps.”

Supercells, the thunderstorms spawning most tornadoes, can punch through the troposphere, creating an overshooting top. Winds moving over and around the storm top can kick up streams of water vapor and ice, which shoot to the stratosphere forming an Above-Anvil Cirrus Plume (AACP). The rising air of the overshooting top then speeds back down to the troposphere while air is flowing over the dome in the stratosphere and then racing down the sheltered side.

Using computer simulations, the researchers found this excites a downslope windstorm with speeds exceeding 240 miles per hour. The study suggests a hydraulic jump, the same mechanism that leads water speeding down a dam’s spillway to burst into froth upon joining slower moving water below, can also be triggered by fluid obstacles in the atmosphere.

Understanding how and why plumes occur above thunderstorms could help forecasters issue more accurate warnings without relying on Doppler radar systems, which could fail in these storms.

NASA research aircraft can now observe the 3D winds at the tops of thunderstorms, but have not yet closely observed AACP production.



We have the technology now to verify our modeling results to see if they’re reasonable. That’s really a sweet spot in science.

— Morgan O’Neill, assistant professor of Earth System Science



O’Neill, M. E., Orf, L., Heymsfield, G. M., & Halbert, K. (2021). Hydraulic jump dynamics above supercell thunderstorms. *Science*, 373(6560), 1248–1251.



Carl Manning/American Red Cross

Nitrate in Drinking Water Linked to Preterm Birth

In a study of 1.4 million California births, Stanford researchers found that women exposed to higher levels of nitrate in drinking water were more likely to deliver very early. Early preterm births, where an infant is born at least nine weeks early, are medically severe, typically require long hospitalizations, and can involve complications with vision, hearing, digestive function and neurological development.

The study, published in *Environmental Health Perspectives*, found that the risk of early preterm birth more than doubled for women whose tap water had nitrate levels that exceeded the federal limit of 10 milligrams per liter compared with those who had nitrate levels were less than 5 milligrams per liter. Among those exposed to a moderate level of 5-10 milligrams per liter of nitrate in their water, the risk increased by half. Births where an infant arrives three to eight weeks early were also associated with elevated nitrate, but the connection is not as strong.

Low level nitrate in groundwater can be naturally occurring but agricultural runoff containing fertilizer and animal waste can greatly increase it. The impact of nitrate on prematurity risk was strongest in California's agricultural regions, where a higher proportion of births are to Hispanic women, explained Allison Sherris, graduate student in Stanford's Emmet Interdisciplinary Program in Environment and Resources. "This is one of many environmental justice issues facing women in rural California."

This interdisciplinary work also involved Mike Baiocchi, assistant professor of Epidemiology and Population Health, Scott Fendorf, professor of Earth System Science, Stephen Luby, professor of Medicine, biostatistician Wei Yang, and Gary Shaw, professor of Pediatrics, who was senior author of the study.

Sherris, A. R., Baiocchi, M., Fendorf, S., Luby, S. P., Yang, W., & Shaw, G. M. (2021a). Nitrate in Drinking Water during Pregnancy and Spontaneous Preterm Birth: A Retrospective Within-Mother Analysis in California. *Environmental Health Perspectives*, 129(5).



We found that higher concentrations of nitrate in drinking water during pregnancy were associated with an increased risk of spontaneous preterm birth, even at nitrate concentrations below the federal regulatory limit.

— Allison Sherris, graduate student in Stanford's Emmet Interdisciplinary Program in Environment and Resources



Kryzhov/Shutterstock



Cautious Pursuit of Solar Geoengineering Research

With the urgent need to address the risks from climate change, a report from the National Academies of Sciences, Engineering, and Medicine, urges the U.S. to pursue a research program for solar geoengineering “in coordination with other nations, subject to governance, and alongside a robust portfolio of climate mitigation and adaptation policies.” The report, written by a committee chaired by Chris Field, director of the Stanford Woods Institute for the Environment, made clear that solar geoengineering, which refers to strategies designed to cool the planet by adding small reflective particles to the upper atmosphere, increasing reflective cloud cover in the lower atmosphere, or thinning high-altitude clouds that can absorb heat, was not a substitute for reducing greenhouse gas emissions.

The report warns that though solar geoengineering strategies have the potential to reduce global temperatures, they could also have a variety of negative consequences.

“The U.S. solar geoengineering research program should be all about helping society make more informed decisions,” said Field. “As we continue to make slow progress in addressing climate change, we urgently need to understand the full range of options for alleviating its harms.”

The report discusses that a U.S. research program focused on solar geoengineering should attempt to enhance policymakers’ understanding of climate response options and improve understanding of technical feasibility, potential impacts on society and the environment, public



Felix Mittermeier

perceptions, and possible social responses. The research agenda can be grouped into the broad areas of investigation of context and goals for solar geoengineering research, impacts and technical dimensions, and social dimensions.

However, this research program should not be designed to advance deployment of these interventions.

Field, C., Cheung, W., Dilling, L., Frumhoff, P., Greely, H., Hordequin, M., Hurrell, J., Light, A., Lin, A., MacMartin, D., McHenry, R., Moreno-Cruz, J., Ricke, K., Russell, L., Sagar, A., & Wennberg, P. (2021). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. National Academies of Sciences, Engineering, and Medicine. Washington, DC: The National Academies Press.

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Based on all of the evidence from social science, natural science, and technology — this research program could either indicate that solar geoengineering should not be considered further, or conclude that it warrants additional effort.

— Chris Field, director of the Stanford Woods Institute for the Environment
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Sea-Level Rise Adaptation

Efforts to fight sea-level rise could end up making flooding worse for neighboring communities, according to a Stanford Natural Capital Project study, published in *Proceedings of the National Academy of Sciences*.

Focusing on the Bay Area, the research shows how seawalls constructed along the San Francisco Bay shoreline could increase flooding and cause hundreds of millions of dollars in damages for communities across the region. The researchers stress that non-traditional approaches, such as choosing to flood certain areas of land rather than build walls, are smarter, more sustainable solutions for the Bay Area and similar communities.

“It’s not practical to keep building taller and taller seawalls to hold back the ocean,” said Anne Guerry, chief strategy officer and lead scientist at the Stanford Natural Capital Project and senior author on the paper. “Our goal was to show how the threat of sea-level rise is interconnected with the whole social-ecological system of the Bay Area. Communities need to coordinate their approaches to sea-level rise adaptation so we can find solutions that are best for the whole bay.”

Using complex mathematical models to map how floodwaters and economic damages would occur depending on where seawalls were, the researchers found that blocking certain areas of shoreline would be particularly damaging. If a seawall were built along the San Jose shoreline, for example, communities would face \$723 million in added flood damage costs from just one high tide. Walling shorelines can also cut off bird and fish species habitat, limit carbon storage and create water quality issues.

Bay Area communities must work together to identify the places where nature-based solutions like flooding make the most sense, explained the researchers. Avoiding adaptation plans that add more pressure to low-income communities by forcing them to move or creating economic hardship is key.

Hummel, M. A., Griffin, R., Arkema, K., & Guerry, A. D. (2021). Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks. *Proceedings of the National Academy of Sciences of the United States of America*, 118(29).

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Our plans should be as interconnected
as our ecosystems.
”

— Anne Guerry, chief strategy officer and lead scientist
at the Stanford Natural Capital Project



Robert Couse-Baker

Rising Seas and Rising Inequality

Sea-level rise threatens many Bay Area communities with high costs from flood damage but those that cannot afford to pay for these damages are particularly vulnerable. In San Mateo County, California, several communities, including half the households in East Palo Alto, are at risk of financial instability from existing social factors or anticipated flooding through 2060, according to a study by Stanford researchers published in *Earth's Future*. Incorporating socioeconomic data on neighborhood groups, the study found that even with flood insurance, these residents would not be able to pay for flood damages which could lead to homelessness or bankruptcy.

“These are workers that make a city run, they’re the heart and soul of an urban operation. If you displace a significant majority too far outside the urban area, the functionality of that city crumbles,” said senior author Jenny Suckale, assistant professor of Geophysics.

The researchers developed the Stanford Urban Risk Framework (SURF) model, which focuses on the residents most likely to lose their livelihoods when water inundates their homes, rather than only looking at the monetary damage to physical structures. In some coastal communities, over 50% of households will face financial instability.

“It was surprising to see in the data how much more lower-income households were affected as a proportion of their income and just how unsustainable it is for those types of households to absorb these costs,” said lead study author Avery Bick, former Masters student in Civil and Environmental Engineering.

The researchers collaborated with government and local stakeholders to develop an equitable approach to sea-level rise adaptation planning that frames the dollar-amount damage relative to what people are able to pay. The co-authors hope this method can be used in other regions vulnerable to coastal flooding or for understanding different climate hazards through an equitable lens.

Bick, I. A., Santiago Tate, A. F., Serafin, K. A., Miltenberger, A., Anyansi, I., Evans, M., Ortolano, L., Ouyang, D., & Suckale, J. (2021). Rising Seas, Rising Inequity? Communities at Risk in the San Francisco Bay Area and Implications for Adaptation Policy. *Earth's Future*, 9(7), e2020EF001963.

If you just look at the dollar amount, you’re missing one major component of the problem. What might be a nuisance in some communities is life-changing in other communities — it’s really about the proximity to a tipping point.

— Jenny Suckale, assistant professor of Geophysics



Wikimedia

Identifying Brick Kilns with Satellite Imagery

It is exceedingly difficult for governments in poor countries to monitor for environmental compliance. A Stanford-led study developed a new machine learning approach using satellite imagery to pinpoint highly polluting brick kilns in Bangladesh that could provide a low-cost solution for environmental regulators.

“Brick kilns have proliferated across Bangladesh to supply the growing economy with construction materials, which makes it really hard for regulators to keep up with new kilns that are constructed,” said co-lead author Nina Brooks, a postdoctoral associate at the University of Minnesota’s Institute for Social Research and Data Innovation who did the research while a Ph.D. student at Stanford.

Coal burning at brick kilns is responsible for 17% of Bangladesh’s total annual carbon dioxide emissions, and half of the air pollutant PM2.5 in Dhaka.

The paper, published in *Proceedings of the National Academy of Sciences*, developed a highly accurate algorithm that identifies whether images contain kilns, learns to localize kilns within the image, rebuilds kilns that have been fragmented across multiple images, and identifies when multiple kilns are contained within a single image. The researchers can also distinguish between banned and legal kiln technologies based on shape classification.

The researchers found that more than three-fourths of kilns in Bangladesh are illegally constructed within 1 kilometer of a school, and almost 10% are illegally close to health facilities. The government systematically underreports kilns in terms of regulations and overreports kilns using a legal as opposed to banned approach. The researchers also found higher numbers of registered kilns in districts adjacent to the banned districts, suggesting kilns are formally registered in the districts where they are legal but constructed across district borders.

Lee, J., Brooks, N. R., Tajwar, F., Burke, M., Ermon, S., Lobell, D. B., Biswas, D., & Luby, S. P. (2021). Scalable deep learning to identify brick kilns and aid regulatory capacity. *Proceedings of the National Academy of Sciences of the United States of America*, 118(17).



Scott Wallace / World Bank



Navaim



“Air pollution kills seven million people every year. We need to identify the sources of this pollution and reduce these emissions.

— Stephen Luby, senior author and professor of Medicine

Dipankar Sarkar



Scott Wallace / World Bank



Navaism

Trees Shifting Ranges in a Changing Climate

As the climate changes, animal and plant species are shifting their ranges toward more suitable conditions. Wildfire is accelerating the process of tree species shifting as climate conditions change, especially toward cooler or wetter sites, according to a Stanford study published in *Nature Communications*. The findings have implications for policymakers and land managers engaged in discussions on forest restoration and wildfire risk reduction.

“Complex, interdependent forces are shaping the future of our forests,” said lead author Avery Hill, Ph.D. student in Biology. “We leveraged an immense amount of ecological data in the hopes of contributing to a growing body of work aimed at managing these ecosystem transitions.”

The study utilized U.S. Forest Service data collected from over 74,000 plots across nine states and identified tree species that are shifting their ranges toward cooler, wetter sites. The researchers compared the rate of range shifts between places that were burned by wildfire and places that were not.

Of eight species that had seedlings growing in climates significantly different from mature trees of the same species, the researchers found that Douglas fir and canyon live oak had larger range shifts in areas that burned than in areas that did not. The analysis did not show how wildfire accelerates range shifts for these trees, but hypothesized that burned areas with open canopies and scorched understory offer less competition from other plants.



The study finds that fire can accelerate tree migration and some species may be slowing the range shifts of others through competition. This raises concerns about the impact of fire management on trees' ability to adapt, and highlights the importance of prescribed and natural fires.

Hill, A. P., & Field, C. B. (2021). Forest fires and climate-induced tree range shifts in the western US. *Nature Communications*, 12(1), 1–10.

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This study highlights a natural mechanism that can help forests remain healthy, even in the face of small amounts of climate change.

— Chris Field, director of the Stanford Woods Institute for the Environment
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Kimberley Davis



Methane as a Food Security Solution

Converting methane, a potent greenhouse gas, into food could turn a climate warming problem into a food security solution. In a study published in *Nature Sustainability*, Stanford researchers evaluated the market potential of feeding captured methane to bacteria and having it grow into protein-rich fishmeal. The analysis found production costs involving methane captured from certain sources in the U.S. are lower than the market price for conventional fishmeal. The work also points out feasible cost reductions that could enable the approach's profitability using other methane sources and also make it capable of meeting all global fishmeal demand.

"Despite decades of trying, the energy industry has had trouble finding a good use for stranded natural gas," said study co-author Evan David Sherwin, postdoctoral researcher in Energy Resources Engineering. "Once we started looking at the energy and food systems together, it became clear that we could solve at least two longstanding problems at once."

Methane-consuming bacteria, called methanotrophs, can be grown in a chilled, water-filled bioreactor and fed pressurized methane, oxygen and nutrients like nitrogen, phosphorus and metals. The result is a protein-rich biomass that can be used as fishmeal in aquaculture feed, offsetting demand for fishmeal made from small fish or plant-based feeds that require more resources.

"While some companies are doing this already with pipeline natural gas as feedstock, a preferable feedstock would be methane emitted at large landfills, wastewater treatment plants and oil and gas facilities," said study co-author Craig Criddle, professor of Civil and Environmental Engineering. "This would result in multiple benefits, including lower levels of a potent greenhouse gas in the atmosphere, more stable ecosystems and positive financial outcomes."



W.carter



Bill McChesney

This work also involved lead author Sahar El Abbadi, lecturer in Stanford's Civic, Liberal and Global Education program, Adam Brandt, associate professor of Energy Resources Engineering, and Stephen Luby, professor of Medicine.

El Abbadi, S. H., Sherwin, E. D., Brandt, A. R., Luby, S. P., & Criddle, C. S. (2021). Displacing fishmeal with protein derived from stranded methane. *Nature Sustainability*, 5(1), 47–56.

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Once we started looking at the energy and food systems together, it became clear that we could solve at least two longstanding problems at once.

— Evan David Sherwin, postdoctoral researcher in Energy Resources Engineering

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Spencer Neuharth / USFWS



Brataffe

Impacts of Extreme Melt for Ice Sheets

One season of extreme ice melt on the Greenland Ice Sheet can reduce the ice sheet's capacity to store future meltwater, which increases the likelihood of future melt going into the sea and raising global sea levels, according to a Stanford study published in *Nature Communications*.

Using ice-penetrating radar data, Stanford scientists revealed the long-term impact of the 2012 extreme melt, which was caused by warm temperatures and high atmospheric pressure over Greenland. The melt left behind a contiguous layer of refrozen ice inside the snowpack, which reduced the ice sheet's ability to store future meltwater.

Through advanced modeling, the team was able to reanalyze airborne ice-penetrating radar data collected by NASA's Operation IceBridge from 2012 to 2017 to interpret melt near the surface of the ice sheet. Ice sheet regions that haven't had extreme melt can store meltwater in the upper 150 feet, preventing it from flowing into the sea, but the researchers found that a melt layer like the one from 2012 can reduce the storage capacity to about 15 feet in some areas.



Longer term, the meltwater that is unable to be stored in the upper part of the ice sheet may drain down to the ice bed, creating slippery conditions that speed up the ice and calving, speeding sea level rise.

“This is really one of the first cases where you can say, shockingly, in some ways, these slow, calm ice sheets care a lot about a single extreme event in a particularly warm year,” said the study’s senior author Dustin Schroeder, associate professor of Geophysics.

Culberg, R., Schroeder, D. M., & Chu, W. (2021). Extreme melt season ice layers reduce firn permeability across Greenland. *Nature Communications*, 12(1), 1–9.



When you have these extreme, one-off melt years, it’s not just adding more to Greenland’s contribution to sea-level rise in that year — it’s also creating these persistent structural changes in the ice sheet itself.

— Riley Culberg, Ph.D. candidate in Electrical Engineering



U.S. Coast Guard

Incorporating Blue Carbon in Climate Policy

Tidal marshes, seagrass beds, estuaries, and other coastal ecosystems provide protection from floods and storms, habitats for fish and birds, and opportunities for recreation, and may also help address climate change.

A study from Stanford's Center for Ocean Solutions (COS) and Natural Capital Project published in *Global Environmental Change* looked at habitats along California's coast and their potential for carbon sequestration.

In order to reach net zero greenhouse gas emissions by 2045, California will have to take advantage of negative emissions opportunities. Ecosystems, coastal and marine habitats that capture and store carbon in soil and plant matter, known as "blue carbon" ecosystems, include salt marshes, seagrass beds, and mangroves. The policy community has focused on forest ecosystems for carbon sequestration,

while overlooking blue carbon habitats, which can store over ten times more carbon than terrestrial ecosystems like forests. This ability makes these habitats a valuable asset in achieving negative emissions goals.

Using the InVEST Coastal Blue Carbon Model developed by the Natural Capital Project, the research team estimated potential carbon sequestration and the economic value of that sequestration in Humboldt Bay, Elkhorn Slough, and the Tijuana River Estuary.

Carbon sequestration services of the tidal marsh habitat at Elkhorn Slough were projected to be worth \$4.8 million to \$9.7 million in the state's carbon market value by 2100. These estimates inform policy recommendations on including blue carbon habitats in California's climate policy and land use planning.



Don DeBoid

“As carbon markets become more prevalent and demands on the coastline intensify, the mapping and valuation of blue carbon habitats can help managers to prioritize carbon sequestration hot spots for coastal conservation or restoration,” said lead author Lisa Wedding, former COS research associate.

Wedding, L. M., Moritsch, M., Verutes, G., Arkema, K., Hartge, E., Reiblich, J., Douglass, J., Taylor, S., & Strong, A. L. (2021). Incorporating blue carbon sequestration benefits into sub-national climate policies. *Global Environmental Change*, 69, 102206.

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Coastal habitats play a critical role in mitigating the drivers of, and impacts from, a changing climate.
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— Eric Hartge, research development manager at Stanford’s Center for Ocean Solutions



The Blue Food Assessment

Global demand for blue foods, such as fish, shellfish and algae, is likely to double by 2050, according to a comprehensive review by more than 100 global experts focused on the potential for creating a healthier, more sustainable, equitable and resilient global food system.

The Blue Food Assessment, a joint initiative led by Stanford's Center for Ocean Solutions (COS) and Center on Food Security and the Environment, along with the Stockholm Resilience Centre and EAT, is a set of scientific analyses that outline challenges and opportunities for fisheries and aquaculture. The goal of the work is to support decision-makers in evaluating trade-offs and implementing well-designed policies and investments for blue foods.

These studies highlight the challenges of blue foods, such as minimizing aquaculture's environmental footprint, and the opportunities they offer, such as feeding more people a greater range of nutrient-rich foods.

Tigchelaar, M., Cheung, W. W. L., Mohammed, E. Y., Phillips, M. J., Payne, H. J., Selig, E. R., Wabnitz, C. C. C., Oyinlola, M. A., Frölicher, T. L., Gephart, J. A., Golden, C. D., Allison, E. H., Bennett, A., Cao, L., Fanzo, J., Halpern, B. S., Lam, V. W. Y., Micheli, F., Naylor, R. L., ... Troell, M. (2021). Compound climate risks threaten aquatic food system benefits. *Nature Food*, 2(9), 673–682.



The global food system is failing billions of people. Blue foods can play a critical role in improving nutrition, livelihoods and ecosystems.

— Rosamond Naylor, professor of Earth System Science



Rising and Shifting Demand

One of the studies, published in *Nature Communications*, estimates global fish consumption by 2050 will increase nearly 80% and the total weight of the world's fish harvest may nearly double as a result of population growth, local changes in affordability and other factors. Because data on the types of fish that people eat is scant, the researchers analyzed previously published research and food supply data for 72 countries that together account for 80% of all blue food consumption worldwide. They also looked at regional demand for the largest consuming nations within each continent and focused on China, India, Nigeria and Chile to investigate the roles of income, trade, geography, culture and preferences in demand.

“A main result of the paper is that wealth and blue food consumption are not tightly coupled. You don't see people eating more fish overall as they get richer, but the types of fish they eat may change. At low incomes, people consume more blue foods if they're affordable. At high incomes, people eat fish if they have some sort of preference for it: health, or sustainability or just taste,” said Rosamond Naylor, professor of Earth System Science and lead author on the study.

Better data on the types of fish that people eat, sustainable expansion of aquaculture and improved understanding of food's local context will be critical to future planning.

We have a tremendous opportunity to bring species to market that are both environmentally sustainable and nutritious.

— Rosamond Naylor, professor of Earth System Science



Naylor, R. L., Kishore, A., Sumaila, U. R., Issifu, I., Hunter, B. P., Belton, B., Bush, S. R., Cao, L., Gelcich, S., Gephart, J. A., Golden, C. D., Jonell, M., Koehn, J. Z., Little, D. C., Thilsted, S. H., Tigchelaar, M., & Crona, B. (2021). Blue food demand across geographic and temporal scales. *Nature Communications*, 12(1), 1–14.



Small-Scale Fisheries and Aquaculture

Another analysis, published in *Nature Food*, draws on profiles from around the world to provide a blueprint for tailoring effective policy to the small-scale fisheries and aquaculture, which provide 90% of the jobs in the blue foods sector. The sector faces growing threats to its existence, including a history of policies that marginalize smaller producers and favor large corporations.

The study led by researchers at Stanford and other institutions shows how the diversity of these artisanal, often family-run businesses makes them more resilient to global shocks such as a pandemic, and also innovative, equitable and sustainable.

“The pandemic has been a giant shock to our global food system,” said study co-lead author Fiorenza Micheli, professor of Biology and co-director of COS and Hopkins Marine Station. “Small-scale fishery and aquaculture operations have proven their resilience and value, but they still need help to thrive amid environmental and economic changes.”

The researchers drew on 70 case studies from around the world and assessed operations according to a framework of attributes including investment level, diversity of products and distance to consumers. This provides the basis for understanding how small-scale fishery and aquaculture operations are affected by climate change, other threats, and specific policies.

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By shedding light on the diverse roles and contributions of such fishers and farmers, we can help raise their profile and set the stage for targeted policy interventions to sustain them into the future.

— Lucie Hazen, Stanford’s Center for Ocean Solutions

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Short, R. E., Gelcich, S., Little, D. C., Micheli, F., Allison, E. H., Basurto, X., Belton, B., Brugere, C., Bush, S. R., Cao, L., Crona, B., Cohen, P. J., Defeo, O., Edwards, P., Ferguson, C. E., Franz, N., Golden, C. D., Halpern, B. S., Hazen, L., ... Zhang, W. (2021). Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. *Nature Food*, 2(9), 733–741.



Aquatic Foods and Global Health

In a third study, published in *Nature*, researchers at Stanford, Harvard and other institutions around the world developed a first-of-its-kind database highlighting blue food's nutrient richness compared with land-based crops and livestock.

The findings could lead to feeding more people, improving diets and overcoming food system structures that have higher risks for women, children and the elderly.

"An increase in the supply of aquatic foods can pull millions from nutrient deficiencies around the world," said study co-lead author Zach Koehn, early career fellow at COS. "To do so, we need to promote the diversity of aquatic foods arising from sustainable production, incentivize access to affordable foods and prioritize their supply to programs serving nutritionally vulnerable communities."

The researchers compiled a database of aquatic food nutrient composition spanning 3,750 species and hundreds of nutrients, minerals, vitamins and fatty acids. It reveals that the top six categories of nutrient-rich animal-source foods are all aquatic foods, including shellfish, salmon and a variety of pelagic fish, such as sardines.

The Blue Food Assessment (bluefood.earth) is an international joint initiative that brings together over 100 scientists from more than 25 institutions and included five studies published at its initial launch.



Blue foods can and should be a key part of a healthier, more equitable global food system. Our research lays the groundwork for policies and interventions to get there.

— Zach Koehn, early career fellow at Stanford's Center for Ocean Solutions



Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., Matthey, H., Eurich, J. G., Gephart, J. A., Fluet-Chouinard, E., Nyboer, E. A., Lynch, A. J., Kjellefold, M., Bromage, S., Charlebois, P., Barange, M., Vannuccini, S., Cao, L., Kleisner, K. M., ... Thilsted, S. H. (2021). Aquatic foods to nourish nations. *Nature*, 598(7880), 315–320.



Invasive Argentine Ants Impacted by Climate Change

A continuous survey of ants at Stanford's Jasper Ridge Biological Preserve begun in 1993 by Deborah Gordon, professor of Biology, and her graduate students, has found that the distribution of Argentine ants has shrunk as a result of climate change, while native diversity increased and expanded.

The area occupied by Argentine ants shrank by 30% and 27% from 1994 to 2020 in fall and spring surveys, while the distribution of native winter ants expanded 70% during the spring surveys. Two other native ant species declined in at least one season, and another two stayed the same.

The nearly 30-year study, published in *Ecology*, shows that the distribution of Argentine ants in the area has reduced following an extreme drought that occurred from 2012 to 2015. The researchers determined this reduction was directly related to climate change, specifically changes in precipitation and in summer maximum temperatures.

The survey has covered an average of 288 sites twice a year where surveyors go to their assigned locations, look for ants within 20 meters and record the species they see. Ants are integral to ecosystems and disruption of ant populations can have a pervasive effect.

"It's been a project that so many different groups of people at Stanford have been involved with — undergrads, grad students, some of whom are still collaborating on this years later, people from the community," said Gordon. "It's been really great that this one project has pulled in so many different kinds of people and kept us connected."

Couper, L. I., Sanders, N. J., Heller, N. E., & Gordon, D. M. (2021). Multiyear drought exacerbates long-term effects of climate on an invasive ant species. *Ecology*, 102(10), e03476.



I've been looking at the data and I suspected this was happening, but I thought it was too good to be true. It took this analysis to really confirm what we saw. It has been gratifying to see the winter ants push back against the Argentine ants.

— Deborah Gordon, professor of Biology



Dan Quinn, Jasper Ridge Docent



Dan Quinn, Jasper Ridge Docent



Dan Quinn, Jasper Ridge Docent



Dan Quinn, Jasper Ridge Docent

Climate Change Impacts on Weather Predictability

Rising temperatures may intensify the unpredictability of weather in Earth's midlatitudes, according to a Stanford study published in *Geophysical Research Letters*. When the atmosphere warms by even as small as a few degrees Celsius, the limit of reliable temperature, wind and rainfall forecasts falls by about a day.

"Our results show the state of the climate in general has implications for how many days out you can say something that's accurate about the weather," said lead author Aditi Sheshadri, assistant professor of Earth System Science. "Cooler climates seem to be inherently more predictable."

Climate change impacts weather patterns and has been shown to increase the frequency and severity of extreme weather events. However, numerical weather models are still generally able to predict day-to-day weather 3 to 10 days out more reliably due to faster computers, better physical models and more precise measurements.

Using computer simulations of a simplified Earth system and a comprehensive global climate model, the study suggests the window for accurate forecasts in the midlatitudes is several hours shorter with every degree Celsius of warming. This could mean that there is less time to prepare and mobilize for big storms in hotter winters than in colder ones. For precipitation, predictability falls by about a day with every 3°C rise in temperature.



The chaotic nature of Earth's atmosphere imposes insurmountable limits on forecasting, but there is value in understanding its effects. Identifying the intrinsic limit of weather predictability could help find ways to improve models of Earth's climate and atmosphere and improved weather prediction could have socioeconomic benefits that amount to at least \$160 billion per year as estimated by the United Nations' World Meteorological Organization.

Sheshadri, A., Borrus, M., Yoder, M., & Robinson, T. (2021). Midlatitude Error Growth in Atmospheric GCMs: The Role of Eddy Growth Rate. *Geophysical Research Letters*, 48(23), e2021GL096126.

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We're working to understand what sets this finite limit of predictability, and also how it might change in different climates, so people can be prepared for these changes.

— Aditi Sheshadri, assistant professor
of Earth System Science

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Always Shooting

Jordan's Water Crisis

In Jordan, reduced water supplies and a growing population are expected to halve per capita water use by 2100, according to Stanford-led study of the country's deepening water crisis. The analysis, published in the *Proceedings of the National Academy of Sciences*, shows that without intervention, few households will have access to even 10.5 gallons of piped water per person per day. Neighborhoods with low-income residents will see 91% of households living on less than 10.5 gallons daily for 11 consecutive months per year.

Jordan's situation exemplifies challenges elsewhere as a result of climate change, population growth, intensifying water use, demographic shocks and heightened competition for water across boundaries, said study co-author Steve Gorelick, professor of Earth System Science and director of Stanford's Global Freshwater Initiative. The World Health Organization estimates half of the world's population may live in water-stressed areas by 2025.

Flows of the Jordan-Yarmouk river system have declined as a result of upstream diversion in Israel and Syria. In some areas, groundwater levels have dropped by more than 1 meter per year, and a major aquifer along Jordan's border with Saudi Arabia is pumped on both sides heavily. Population growth and waves of refugees are fueling water demand.

Researchers used a computer model of Jordan's freshwater system that simulates interactions with natural processes and human behaviors. Under a range of climate and socioeconomic scenarios, the team quantified the effects of introducing measures such as fixing leaky pipes and eliminating water theft. The model showed that simultaneous efforts to increase supply, reduce demand and reform distribution were likely to deliver exponential improvements to national water security.



UN Photo/Rick Bajornas



Yoon, J., Klassert, C., Selby, P., Lachaut, T., Knox, S., Avisse, N., Harou, J., Tilmant, A., Klauer, B., Mustafa, D., Sigel, K., Talazi, S., Gawel, E., Medellín-Azuara, J., Bataineh, B., Zhang, H., & Gorelick, S. M. (2021). A coupled human-natural system analysis of freshwater security under climate and population change. *Proceedings of the National Academy of Sciences of the United States of America*, 118(14).

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In water-scarce regions where sustainability planning is most needed, it is challenging to think beyond how to distribute scarce freshwater tomorrow, next month, and to some extent, in the next several years. It’s in these places where our long-term policy evaluations are most valuable.

— Steve Gorelick, professor of Earth System Science and director of Stanford’s Global Freshwater Initiative
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PUBLICATIONS

CLIMATE



Abernethy, S., O'Connor, F. M., Jones, C. D., & Jackson, R. B. (2021). Methane removal and the proportional reductions in surface temperature and ozone. *Philosophical Transactions of the Royal Society A*, 379(2210). DOI: 10.1098/RSTA.2021.0104

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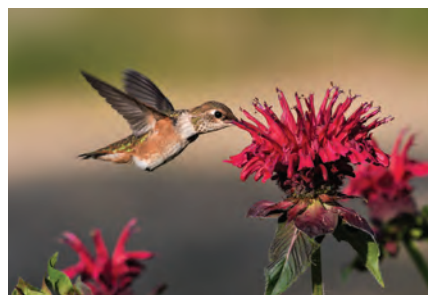
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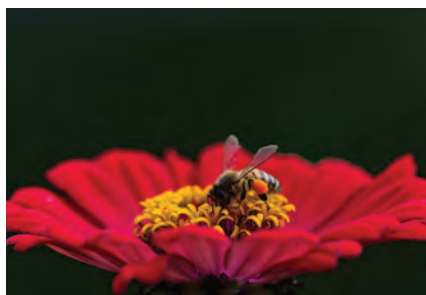
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