STANFORD ENVIRONMENTAL RESEARCH

2020 YEAR IN REVIEW

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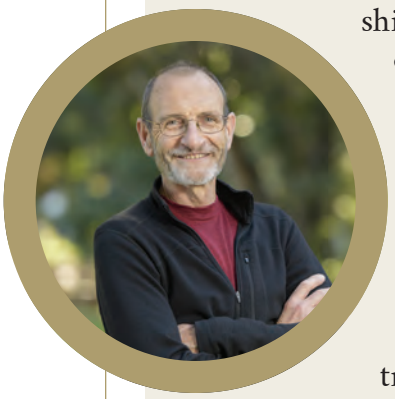
ENVIRONMENT

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

DIRECTOR'S NOTE

With raging wildfires, massive socioeconomic disruption, political upheaval, and a devastating global pandemic, 2020 transformed our understanding of how people affect the environment. It reminded us again and again how fragile our planet, institutions, and lives can be. Yet, throughout this trying time, the Stanford community strived to meet the challenge of the moment with persistence, ingenuity, and grit.

In short order, Stanford researchers began creating innovative community COVID-19 testing methods, making recommendations to government authorities on human behavior around mask wearing, and investigating the effect of pandemic-related lockdowns on the Earth system. As wildfire smoke filled the West, researchers studied how to better prevent and predict fires as well as the health impacts of air pollution. In continuing to understand climate change impacts, researchers focused on ocean acidification, flood risk, drought, and disease shifts. Researchers developed novel solutions, including innovations in desalination, observation technology, climate model improvements, and microbial batteries. Focusing on human and societal connections, scholars unearthed links between rural healthcare and deforestation, as well as youth education and environmental leadership.



The Stanford Woods Institute for the Environment is the interdisciplinary nexus of environmental research and solutions at Stanford and it brings me immense pride to share with you this collection of environmental scholarship, which exemplifies the transformative potential of a 21st century university. This research highlights both Stanford's disciplinary excellence and the tremendous translational impact of coming together as an interdisciplinary community focused on creating solutions for people and the planet.

At the end of a dark and challenging year, there is still much cause for hope. With the announcement of a new school focused on addressing the challenges of sustainability and climate change, I celebrate Stanford's increasing commitment and focus on these pressing issues and look forward to the Woods community's continued leadership in that endeavor.

I await the day we can reconnect in person. Until then, I remain more inspired than ever by our collective resilience.

Chris Field

Chris Field
Perry L. McCarty Director

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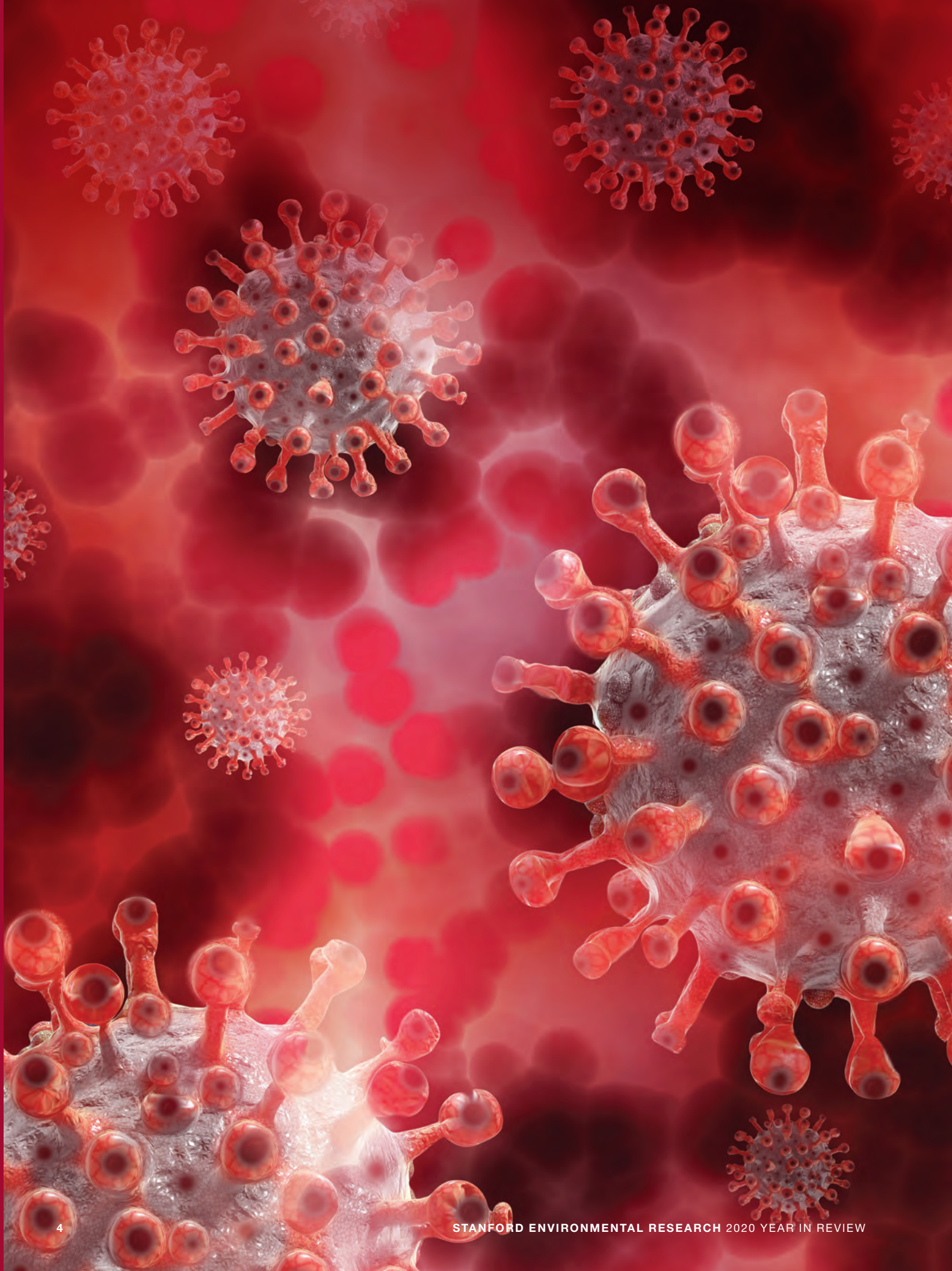


THE COVID-19 PANDEMIC

The COVID-19 pandemic brought the entire world to a standstill and continues to devastate communities, alter economies, and take the lives of thousands per day, all began with a spillover event in which a disease transferred from an animal to a human. It all began as a sobering reminder that interactions between humans and the environment and encroachment on species habitat can have serious downstream effects.

From the start, Stanford environmental researchers have been actively engaged on multiple fronts in understanding, combating and adapting to the COVID-19 pandemic.

Window into the Earth System

The response to the COVID-19 pandemic, which saw communities lock down across the globe, has provided a rare opportunity for studying natural and human systems, according to a Stanford-led perspective published in *Nature Reviews Earth & Environment.*

The researchers hypothesized outcomes of the pandemic's unprecedented socioeconomic disruption from shelter-in-place orders, and outlined research priorities for advancing understanding of humanity's impact on the environment.

"Without distracting from the most important priority – which is clearly the health and well-being of people and communities – the current easing of the human footprint is providing a unique window into the impacts of humans on the environment, including a number of questions that are critical for effective public policy," said lead author Noah Diffenbaugh, professor of Earth System Science.

To understand both short and long-term impacts, researchers focused on pathways involving energy, emissions, climate and air quality, poverty, globalization, and food and biodiversity. For example, models suggest vehicle electrification will improve air quality. With emissions reductions from the lockdown, researchers have data to check how accurate those models are.

"It's critical for us to better understand how future societal disruptions and catastrophes could affect interactions among energy systems and other systems that serve society," said co-author Inês Azevedo, associate professor of Energy Resources Engineering.

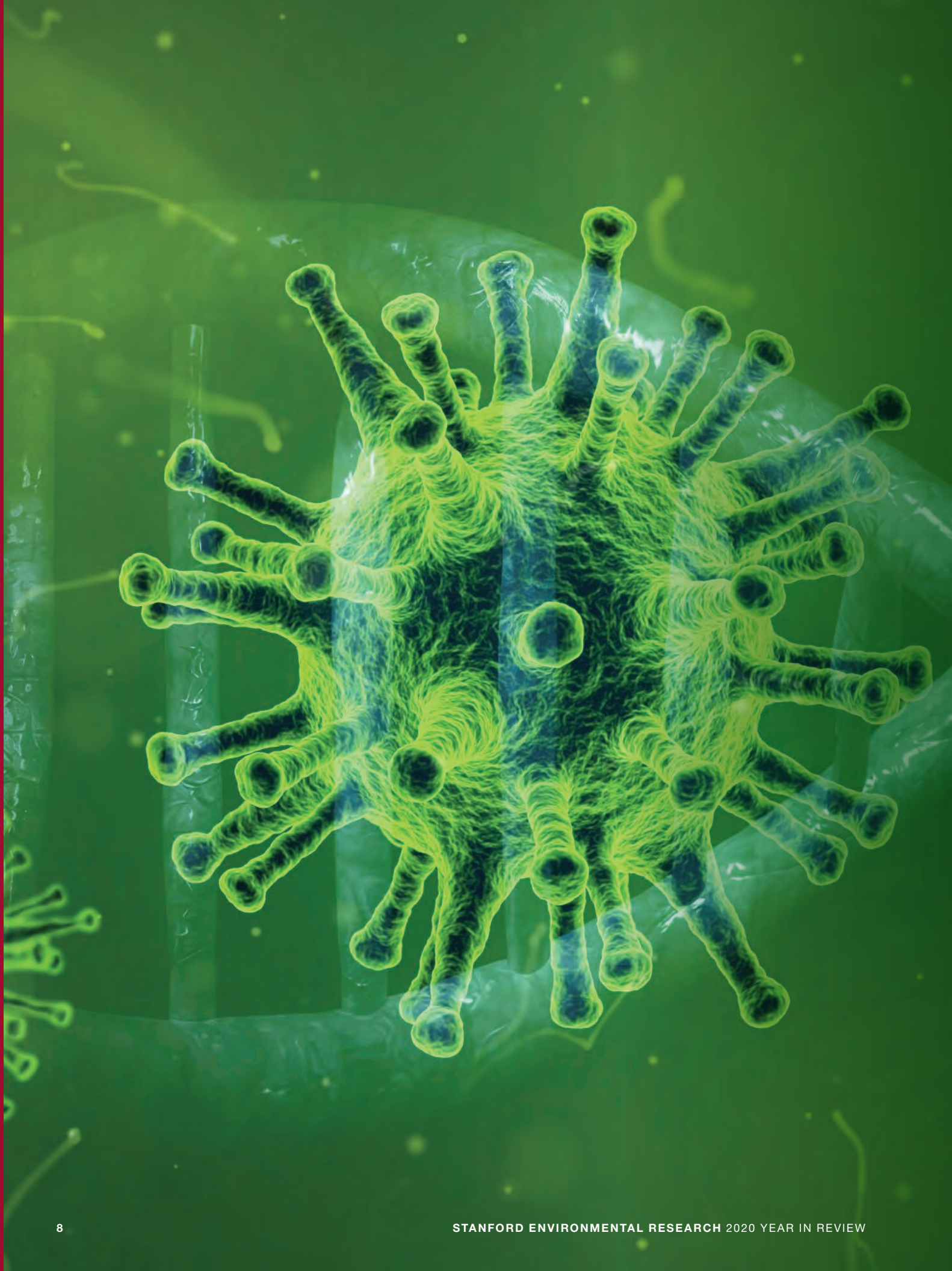
Diffenbaugh, N. S., Field, C. B., Appel, E. A., Azevedo, I. L., Baldocchi, D. D., Burke, M., Burney, J. A., Ciais, P., Davis, S. J., Fiore, A. M., Fletcher, S. M., Hertel, T. W., Horton, D. E., Hsiang, S. M., Jackson, R. B., Jin, X., Levi, M., Lobell, D. B., McKinley, G. A., … Wong-Parodi, G. (2020). The COVID-19 lockdowns: a window into the Earth System. *Nature Reviews Earth & Environment,* 1(9).

> Human behavior contributes to, but is also affected by, changes in the Earth system, and COVID-19 is creating new challenges for ensuring people and corporations act to protect the planet.

— Margaret Levi, professor of Political Science

> COVID-19 poses some of the biggest challenges we have faced in the last century. With every challenge, there are opportunities for learning, and this paper provides a map for expanding the set of opportunities.

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



Testing for COVID-19 in Wastewater

Testing wastewater — a robust source of COVID-19, as those infected shed the virus in their stool — could help track community infections and help enable public health officials to contain the virus. A study co-lead by Stanford researchers shows a method that can detect COVID-19 in wastewater samples while also tracking whether infection rates are trending up or down.

> This work confirms that trends in concentrations of SARS-CoV-2 RNA in wastewater tracks with trends of new COVID-19 infections in the community. Wastewater data complements the data from clinical testing and may provide additional insight into COVID-19 infections within communities.
>
> *— Alexandria Boehm, professor of Civil and Environmental Engineering*

Tracking COVID-19 through wastewater surveillance of RNA could alert decision-makers about potential outbreaks days before those infected recognize symptoms. The viral RNA can be isolated from sewage in wastewater treatment facilities and identified through a complicated recovery process, with the relative amounts in wastewater correlating to the number of cases. Wastewater sampling is an inclusive source of information about infections because anyone with a toilet connected to a sewer system could be depositing biological samples on a regular basis.

Researchers sought to compare the ability to detect the virus in a mostly liquid influent or settled solid form of wastewater. Though most current research focuses on influent samples, the team found the settled solid samples had higher concentrations and better detection of SARS-CoV-2. The researchers tested samples from the San Jose-Santa Clara Regional Wastewater Facility from mid-March to mid-July 2020, tallying daily concentration numbers and using statistical modeling, compared these with COVID-19 confirmed cases. Their results tracked the trend of the county's cases.

The research presents a possible way to inform public health interventions by identifying outbreaks, hotspots, and case trends. Alexandria Boehm, professor of Civil and Environmental Engineering, co-lead the research with Krista Wigginton, associate professor at the University of Michigan.

Graham, K. E., Loeb, S. K., Wolfe, M. K., Catoe, D., Sinnott-Armstrong, N., Kim, S., Yamahara, K. M., Sassoubre, L. M., Mendoza Grijalva, L. M., Roldan-Hernandez, L., Langenfeld, K., Wigginton, K. R., & Boehm, A. B. (2021). SARS-CoV-2 RNA in Wastewater Settled Solids Is Associated with COVID-19 Cases in a Large Urban Sewershed. *Environmental Science & Technology, 55*(1), 488–498.

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Mask Confusion

With duel crises of wildfire smoke and the COVID-19 pandemic, public health guidance on mask wearing is becoming increasingly important. In a perspective published in *Environmental Research Letters*, Stanford researchers drew on studies of human behavior, past epidemics and reactions to wildfire smoke to make recommendations for communicating correct mask use and directing future research.

"It's really important for public health officials at the local or state level to provide clearer guidance to the public about which masks are appropriate for which events, and to make recommendations for behavior change," said Francisca Santana, a Ph.D. candidate in the Emmett Interdisciplinary Program in Environment and Resources and lead author of the review.

In addition to a number of recommendations for U.S. government agencies, the researchers stressed the importance of incorporating the social and psychological influences of mask use behavior. Social norms can include comparing people's actions to others, providing positive feedback and strategically placing messaging.

"Even people who understand what they should be doing are not doing it," said senior author Gabrielle Wong-Parodi, assistant professor of Earth System Science. "The message needs to be evidence-based, and we need to provide people with behaviorally realistic options that they can actually do and afford."

Through interviews, the researchers found mask wearing mistakes such as an asthmatic wearing a mask while sleeping, which can stress breathing. The researchers also looked at China and Japan, where benefits of masks are strongly perceived. There is also research on how masks indicate political affiliation in the U.S.

Santana, F. N., Fischer, S. L., Jaeger, M. O., & Wong-Parodi, G. (2020). Responding to simultaneous crises: communications and social norms of mask behavior during wildfires and COVID-19. *Environmental Research Letters, 15*(11).

> Your perception of the behavior of people you're in close contact with matters maybe even more than what they're actually doing, in terms of influencing your own behavior.
>
> *— Gabrielle Wong-Parodi, assistant professor of Earth System Science*

Ian Sane

Babette Plana

Ivan Radic

Carbon Emissions in Wake of COVID-19

In the wake of the COVID-19 pandemic and related lockdown, global carbon dioxide (CO_2) emissions are down dramatically. A study by the Global Carbon Project, an initiative led by Rob Jackson, professor of Earth System Science, found daily CO_2 emissions have dropped by as much as 17% globally. The research compiles government policies and activity data to pinpoint where energy demand has dropped off the most and to estimate the impact on annual emissions.

"The drop in global emissions we estimate this year will surprise some people in being "only" 4 to 7% because shelter-in-place rules are temporary and staggered across different countries. But it will still be the biggest emissions drop since World War II, though for undesirable and unsustainable reasons," explained Jackson.

The study found that emissions at their peak in individual countries decreased by 26% on average. The estimates on 2020 annual emissions depend on how long lockdowns last. The more restrictions and the longer they last, the lower the energy demand and related CO_2 emissions. Jackson discussed what the pandemic can teach us about behavior change in the long run.

Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J. P., Abernethy, S., Andrew, R. M., De-Gol, A. J., Willis, D. R., Shan, Y., Canadell, J. G., Friedlingstein, P., Creutzig, F., & Peters, G. P. (2020). Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nature Climate Change*, 10(7), 647–653.

> COVID-19 may change commuting and transportation permanently. Cities from Milan to Seattle are closing miles of streets to traffic permanently and opening them to pedestrians and bicyclists. Telecommuting, even part-time, might be the new normal.
>
> *— Rob Jackson, professor of Earth System Science*

RESEARCH AWARDS FOR ENVIRONMENTAL SOLUTIONS

Focused on bringing together diverse interdisciplinary groups of scientists, engineers, sociologists, lawyers, and other experts, the Stanford Woods Institute for the Environment has for 16 years funded projects that look for innovative ways to solve pressing environmental challenges.

The Environmental Venture Projects (EVP) and Realizing Environmental Innovation Program (REIP) grants provide support for new ideas that address problems, such as ocean acidification, groundwater contamination, waste management, and wildfires, that cannot be solved by any one field of expertise. These cross-cutting projects create practical solutions with a focus on cost efficiency, high returns, and potential to scale.

Since the EVP program began in 2004 and the REIP program began in 2015, the Stanford Woods Institute has awarded more than $17 million in grants to 112 research teams representing all seven of Stanford's academic schools.

ENVIRONMENTAL VENTURE PROJECTS

EVP grants support interdisciplinary, high-risk research projects that identify and develop real-world solutions. The projects selected for 2020 will receive grants of up to $200,000 over the next two years:

Safeguarding Ocean Ecosystems and Food Security: Coastal communities throughout the world depend on wild-caught fisheries and productive near- and offshore ecosystems. A recent ban on fishing in Palau covering 80% of its waters provides an unprecedented opportunity to investigate biophysical, cultural and socioeconomic linkages among Palau's offshore and nearshore ecosystems and coastal communities. The results could provide other small island nations valuable insights on safeguarding ocean ecosystems and food security. The investigation will also illuminate connections between tropical communities and marine ecosystems, as well as the role of Marine Protected Areas in environmental conservation and human development. Fiorenza Micheli (Biology), Nicole Ardoin (Education), Rob Dunbar (Earth System Science), Stephen Monismith (Civil and Environmental Engineering) and Krish Seetah (Anthropology)

Strengthening Coral Reefs: Up to half of the world's coral reefs have been destroyed by ocean warming. However, some corals have managed to remain resistant to high temperatures. Discovering the mechanism for that resistance could open a window to restoring reefs. This project uses a novel approach that alters coral physiology with a battery of drugs developed for cancer and cell technology research. High throughput testing of thousands of chemicals using a new coral tissue model will show the cellular mechanisms that circumvent bleaching at high temperatures. Selection for those specific mechanisms in current populations of corals will help restore future reefs with enhanced heat tolerance. Stephen Palumbi (Biology), Bo Wang (Bioengineering) and Yunzhi Peter Wang (Medicine)

Optimizing Environmental Communication: Public support for environmental issues and solutions can be significantly influenced by the terms used to communicate them. This project, informed by data-driven natural language processing methods, interviews and focus groups, deploys a set of new terms, with the aim to create a data-driven lexicon that is either more likely to increase support for environmental practices and policies or less politically divisive. The researchers hope to create a data-driven environmental lexicon that engages support for pro-environmental policies and practices. Brian Knutson (Psychology), Nicole Ardoin (Education) and Dan Jurafsky (Linguistics)

Voices of the Earth: Fostering environmental awareness among the public is key to addressing the systemic causes of environmental destruction. This project involves a staged reading exploring the relationship between human beings and the natural world through a merging of scientific research, poetic wisdom, political activism, climate-change denials, and environmental writing from indigenous communities. The production will be made available online for interested groups to access, perform and use as an organizing tool to promote broader awareness of the climate crisis. Researchers will measure the efficacy of this effort to make environmental challenges approachable and understandable. Rush Rehm (Theater and Performance Studies, and Classics) and Charles Junkerman (Comparative Literature)

Incentivizing an End to Deforestation: One of the leading sources of greenhouse gas emissions is deforestation. A significant percentage of deforestation is due to smallholder farmers in developing countries clearing land and this causes huge losses in biodiversity. This project seeks to reduce deforestation by smallholders by providing direct payments to farmers for conserving forest assets and using information- and market-based approaches to improve smallholder farmer livelihoods by enhancing the effectiveness of similar, traditional schemes. The researchers will work in collaboration with partners in Uganda and Indonesia to demonstrate the efficacy of these approaches in achieving higher environmental outcomes while improving smallholder livelihood. Irene Lo (Management Science and Engineering), Jim Leape (Woods) and John Weyant (Management Science and Engineering)

Community-Based Agriculture and Aquaculture Restoration: This project collectively engages community members in Hawaii in place-specific native eco-and food-system restoration, social and cultural regeneration educational experiences and applied research and data collection. Collaborating with local partners, researchers will establish a baseline of soil analysis and map existing agricultural features in order to protect, restore and enhance watershed ecosystems. The project will encourage collaborative management plans, and create a model for continued, community-lead efforts into the future. Michael Wilcox (Cultural and Social Anthropology) and Peter Vitousek (Biology)

REALIZING ENVIRONMENTAL INNOVATION PROGRAM

REIP is intended to advance solution-based projects from the discovery phase of research to the validation phase and adoption by end users. The projects selected for 2020 will receive grants of up to $200,000 over the next two years:

Making Agriculture More Sustainable: The process used to manufacture ammonia, a main ingredient in fertilizers, consumes 2% of the world's natural gas and energy, and emits 300 million metric tons of carbon dioxide every year. This project aims to develop a more affordable, sustainable and safe approach. By developing a new process powered by renewable energy, the researchers would eliminate the carbon footprint that has plagued fertilizer production for over a century – while reducing costs and increasing safety. Mark Capelli (Mechanical Engineering) and Juan Rivas (Electrical Engineering)

AI for Clean Water: Partnering with the Environmental Protection Agency, researchers will deploy cutting-edge data science to better improve methods for identifying industrial and other polluters discharging chemicals into water illegally beyond permitted levels. They will develop improved risk models to enable early enforcement interventions and compare effectiveness of different enforcement approaches. The partnership is intended to lead to a broader effort to use data science to tackle a range of environmental compliance challenges. Dan Ho (Law) and Jenny Suckale (Geophysics)

Biosensors for Real-time Sensing of the Marine Environment: This project offers safe, cutting-edge approaches to monitor and assess marine life and ecosystem health to support conservation and management. Current efforts to track marine animals to study the health of marine ecosystems primarily depend on expensive, rigid and heavy tags that require invasive attachment techniques. This project will build a low cost, lightweight, non-invasive tag. Researchers will develop a small wearable multisensory tag capable of withstanding harsh ocean environments. Barbara Block (Biology), Zhenan Bao (Chemical Engineering) and Sherman Lo (Aeronautics and Astronautics)

Richard Masoner

Commute Disruption from Bay Area Coastal Flooding

Coastal flooding has caused traffic disruptions in the San Francisco Bay Area for decades. A new computational model by Stanford researchers shows how coastal flooding will impact commutes in the Bay Area over the next 20 years, revealing communities with sparse road networks will experience the worst delays regardless of how far they are from the coast.

"In disaster science, we usually say the hazard is the elephant in the room and the other things are details, but this study says the elephant in the room is really the existing structure, the existing vulnerability," said senior author Jenny Suckale, assistant professor of Geophysics. "In this case, it's the sparsity of the road network."

The researchers integrated traffic models with regional flood maps to show how commute disruptions spread substantially inland, creating longer delays for communities with sparse road networks compared to areas of flooding. Measuring road network density may be more important for understanding community resilience to commute delays than actual flood exposure, according to the study, which was supported in part through an REIP grant.

With climate adaptation policies often focused locally where hazards strike, the results highlight the importance of creating sustainable practices and thinking more broadly at the regional scale.

Kasmalkar, I. G., Serafin, K. A., Miao, Y., Bick, I. A., Ortolano, L., Ouyang, D., & Suckale, J. (2020). When floods hit the road: Resilience to flood-related traffic disruption in the San Francisco Bay Area and beyond. *Science Advances, 6*(32), eaba2423.

> At a very fundamental level, I think this research asks who is affected by these hazards. We need to be thoughtful about how we manage overflow traffic and how we make sure communities who are already disadvantaged don't suffer disproportionately from this.
>
> — *Jenny Suckale, assistant professor of Geophysics*

Mapping Wildfire Fuel Moisture Across the West

With California and the American West reeling from yet another devasting wildfire season, Stanford researchers are enhancing fire prediction, developing a deep-learning model that maps fuel moisture levels in fine detail across 12 western states.

Historically, estimating fuel moisture content, a factor that influences wildfire risk, has involved informed but unproven guesses about relationships between temperature, precipitation, and plant water content and dryness. Fire agencies typically use a time-intensive process to measure water in dry flammable vegetation in a small number of samples at hundreds of sites nationwide.

"Now, we are in a position where we can go back and test what we've been assuming for so long – the link between weather and live fuel moisture – in different ecosystems of the western United States," said lead author Krishna Rao, Ph.D. candidate in Earth System Science.

The new model uses a recurrent neural network to recognize patterns in field data and estimates fuel moisture from measurements of visible light bouncing off Earth and synthetic aperture radar collected by spaceborne sensors.

> One of our big breakthroughs was to look at a newer set of satellites that are using much longer wavelengths, which allows the observations to be sensitive to water much deeper into the forest canopy and be directly representative of the fuel moisture content.
>
> *— Alexandra Konings, assistant professor of Earth System Science*


Oregon USNG


Bonnie Moreland

The study, which was supported in part by an EVP grant, has the model's estimates feed into an interactive map displaying fuel moisture content that fire agencies may eventually be able to use to prioritize prescribed burns and other control measures.

"Creating these maps was the first step in understanding how this new fuel moisture data might affect fire risk and predictions," said Alexandra Konings, assistant professor of Earth System Science and senior author of the study. "Now we're trying to really pin down the best ways to use it for improved fire prediction."

Rao, K., Williams, A. P., Flefil, J. F., & Konings, A. G. (2020). SAR-enhanced mapping of live fuel moisture content. *Remote Sensing of Environment*, 245, 111797.

Daniel Chodusov

FWC FWR

Climate Impacts on Mosquito-borne Diseases

Climate warming and urbanization will likely lower rates of malaria, while increasing rates of other mosquito-borne diseases, such as dengue and other arboviruses, in Sub-Saharan Africa, according to a Stanford-led study published in Lancet Planetary Health.

> Climate change is going to rearrange the landscape of infectious disease. Chikungunya and dengue outbreaks like we've recently seen in East Africa are only becoming more likely across much of the continent. We need to be ready for this emerging threat.
>
> *— Erin Mordecai, assistant professor of Biology*

Understanding that different species of mosquitoes thrive at various temperature ranges and transmit different diseases, the researchers worked to predict how, when and where in Sub-Saharan Africa malaria will ebb and other mosquito-borne diseases, such as dengue fever, will rise dramatically. Malaria is most likely to spread at 25 degrees Celsius while the risk of dengue is highest at 29 degrees Celsius.

"It's vital to focus on controlling mosquitoes that spread diseases like dengue because there are no medical treatments for these diseases," said senior author Desiree LaBeaud, professor of Pediatrics. "On top of that, a shift from malaria to dengue may overwhelm health systems because diseases introduced to new populations often lead to large outbreaks."

With malaria affecting more than 200 million people in Sub-Saharan Africa, public health efforts in the region have taken aim at nighttime-biting Anopheles gambiae mosquitos which transmit the disease with insecticide-treated bed nets, indoor spraying, and other measures. However, these efforts do not combat the daytime-biting Aedes aegypti mosquito, which can transmit a range of devastating diseases, and has had its range expanded by growing urbanization and climate change. The study, which was supported in part by an EVP grant, warns of a public health disaster if the region fails to supplement its focus on malaria to include strategies tailored to other mosquito-borne diseases.

Mordecai, E. A., Ryan, S. J., Caldwell, J. M., Shah, M. M., & LaBeaud, A. D. (2020). Climate change could shift disease burden from malaria to arboviruses in Africa. In *The Lancet Planetary Health 4*(9), e416–e423.


DFAT

Environmental Leadership for Youth in Rural Costa Rica

Examining the links between community resources and environmental education in Costa Rica's Osa Peninsula, Stanford researchers found that these connections can strengthen students' ability to create meaning and take action in environmental leadership.

The study, published in *Environmental Education Research*, examined the Stanford Environmental Leadership and Language program (SELAL). Developed following four years of INOGO (Osa and Golfito Initiative) community consultation and research, the program seeks to "increase high school students' academic retention and graduation rates, familiarity and relationships with diverse community members, access to relevant jobs in the local and regional tourism and ecotourism economy, knowledge of local environmental challenges, and—as our local partners stated—their 'environmental leadership' with the hope of transforming how youth envision themselves relative to others and their environment," according to the researchers. Eight iterations of SELAL were implemented between 2015 and 2019, engaging 238 underserved high school students ranging from 15- to 21-years-old in the coastal towns Puerto Jiménez and Uvita.

The researchers, led by Nicole Ardoin, professor of Education, and William Durham, professor of Anthropology, used a community-as-pedagogy framework to investigate how pedagogically-positioned social relationships mediate students' knowledge, perceptions, and leadership.

Through SELAL, the team found students showed an increase in knowledge about their local environment, critically and socially engaging with new information and further developing networking skills in the context of community-informed environmental issues.

This work was supported by the Stanford Woods Institute for the Environment and expands on research collaborations from an EVP grant.

Selby, S. T., Cruz, A. R., Ardoin, N. M., & Durham, W. H. (2020). Community-as-pedagogy: Environmental leadership for youth in rural Costa Rica. *Environmental Education Research, 26*(11), 1594–1620.

> After participating in the program, the students describe environmental leadership as requiring persistence, forethought, and a willingness to care for both the environment and community.
>
> — *Study authors*

INOGO

INOGO

Improving Microbial Batteries

Microbial batteries produce energy from wastewater and other organic matter. However, for these microbial electrochemical technologies to be successful in the treatment of wastewater, their power densities need to be increased, and costs need to be decreased.

To address these barriers to scaling up this technology, an interdisciplinary team of Stanford researchers led by Yi Cui, professor of Materials Science and Engineering and director of the Precourt Institute for Energy, and Craig Criddle, professor of Civil and Environmental Engineering, hard wired a microbial community to a growing layer of conductive polypyrrole on a sponge bioanode, an electrode system where electroactive microbial communities catalyze the anodic oxidation reactions of a microbial battery, showing rapid biocatalytic current development at 10 times higher after four hours. Moreover, these hard-wired bioanodes maintained 2 times higher steady-state power density after 28 days.

"The result is a rapid start-up, low-cost, and high volumetric power density system for harvesting energy and carbon from dilute organics in wastewater," wrote the researchers.

With rapid electron turn over in hours instead of days and order of magnitude higher power with microbial batteries than microbial fuel cells, the study, which was supported in part through an EVP grant, demonstrates the benefit of hard-wiring of bioanodes. With an eye to scaling up, the researchers are currently developing a semi-continuous system that alternately flushes wastewater, allowing air to reoxidize the electrodes without having to remove them. The microbial battery system requires no expensive catalysts or membranes and uses a low-cost sponge current collector, lowering overall costs.

The hard-wiring, also known as in vivo polymerization, "enabled the development of a fast-growth stacked microbial battery that could significantly improve the economics and feasibility of microbial electrochemical technologies at scale," according to the researchers.

Dubrawski, K. L., Woo, S. G., Chen, W., Xie, X., Cui, Y., & Criddle, C. S. (2020). In Vivo Polymerization ("Hard-Wiring") of Bioanodes Enables Rapid Start-Up and Order-of-Magnitude Higher Power Density in a Microbial Battery. *Environmental Science and Technology, 54*, 14732–14739.

Timothy Neesam

El Hamouri

SA Water

RESEARCH HIGHLIGHTS

U.S. Corn Yield's Sensitivity to Drought

Climate change is increasing the frequency and severity of droughts in many agricultural regions. Though new management techniques and approaches have allowed the U.S. Corn Belt to increase yields despite some changes in climate, soil sensitivity to drought has increased significantly, according to a Stanford study published in *Nature Food*.

"The good news is that new technologies are really helping to raise yields, in all types of weather conditions," said study lead author David Lobell, professor of Earth System Science. "The bad news is that these technologies, which include some specifically designed to withstand drought, are so helpful in good conditions that the cost of bad conditions are rising. So there's no sign yet that they will help reduce the cost of climate change."

Using county soil maps, satellite-based yield estimates and other data, the researchers examined fields in the U.S. Corn Belt, which accounts for two-thirds of U.S. corn production. By comparing fields along gradients of drought stress each year, they identified how sensitivity to drought is changing over time. Yields were generally higher for soils that held more water and yield sensitivity to soil water storage increased 55% between 1999 and 2018, with larger increases in drier states. Thus, as climate change intensifies, the cost to maintain crop yields will likely increase.

To further research, the team call for increased access to field-level yield data that are measured independently of weather data.

> This study shows the power of satellite data, and if needed we can try to track things from space alone. That's exciting. But knowing if farmers are adapting well to climate stress, and which practices are most helpful, are key questions for our nation. In today's world there's really no good reason that researchers shouldn't have access to all the best available data to answer these questions.
>
> *— David Lobell, professor of Earth System Science*

Lobell, D. B., Deines, J. M., & Tommaso, S. Di. (2020). Changes in the drought sensitivity of US maize yields. *Nature Food, 1*(11), 729–735.

DFAT

Benefits of Diversified Farms

Farms with diverse crops planted together provide more secure, stable habitats for wildlife and are more resilient to climate change than the single-crop standard that dominates the agriculture industry, according to a study published in *Nature* by Stanford researchers.

The study offers a long-term look at how farming practices affect bird biodiversity in Costa Rica. Diversified farms were found to be more stable in the number of birds they support, provide a more secure habitat and shield against the impacts of climate change much more effectively.

"The tropics are expected to suffer even more intensely in terms of prolonged dry seasons, extreme heat and forest dieback under climate change," said senior author Gretchen Daily, director of the Stanford Natural Capital Project and professor of Biology. "But diversified farms offer refuge – they can buffer these harmful effects in ways similar to a natural forest ecosystem."

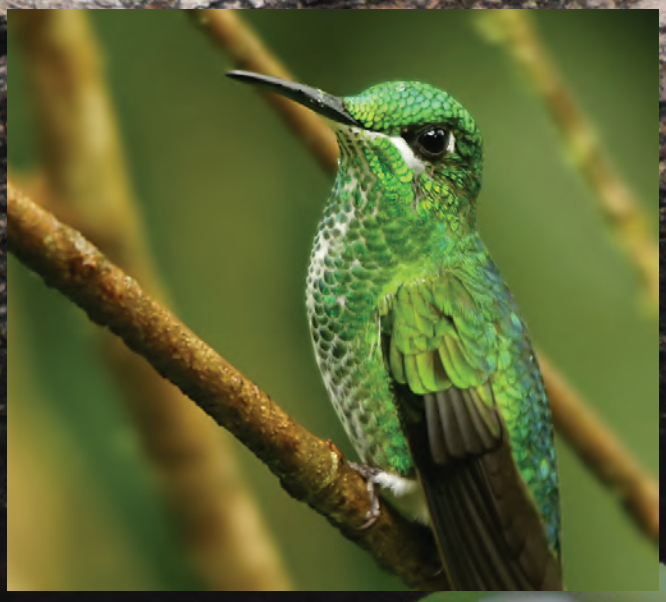
The researchers used nearly 20 years of field data to understand which birds live in natural tropical forests and in different types of farmland. Tropical regions are species-rich, but face the greatest threats to biodiversity. As forests are felled to plant cash crops, natural habitats shrink. Moreover, climate change has resulted in longer, hotter dry seasons that make species survival even more challenging. While in intensive monocrop farmlands, endangered species are declining, in the diversified systems, the endangered birds are found year after year. The work highlights the importance of farms that grow multiple crops in a mixed setting.

Hendershot, J. N., Smith, J. R., Anderson, C. B., Letten, A. D., Frishkoff, L. O., Zook, J. R., Fukami, T., & Daily, G. C. (2020). Intensive farming drives long-term shifts in avian community composition. *Nature, 579*(7799), 393–396.

Nick Hendershot

> This study shows that climate change has already been impacting wildlife communities, continues to do so, and that local farming practices really matter in protecting biodiversity and building climate resilience.
>
> *— Nick Hendershot, Ph.D. candidate in Biology*

Nick Hendershot



Seeing Underwater

By combining light and sound to break through the barrier at the interface of air and water, Stanford engineers have developed an airborne method for imaging underwater objects. The researchers envision their Photoacoustic Airborne Sonar System (PASS) will one day being used to conduct drone-based biological marine surveys from the air, carry out large-scale aerial searches of sunken ships and planes, and map the ocean depths.

"Airborne and spaceborne radar and laser-based, or LIDAR, systems have been able to map Earth's landscapes for decades. Radar signals are even able to penetrate cloud coverage and canopy coverage. However, seawater is much too absorptive for imaging into the water," said Amin Arbabian, associate professor of Electrical Engineering, who led the study published in *IEEE Access*. "Our goal is to develop a more robust system which can image even through murky water."

Only a small fraction of Earth's ocean depths have high-resolution imaging and mapping. Sound waves cannot pass from air into water or vice versa without losing more than 99.9% of their energy through reflection. Electromagnetic radiation, such as light, also loses energy when passing from one physical medium into another through reflection and absorption. This makes underwater mapping from air and space difficult.

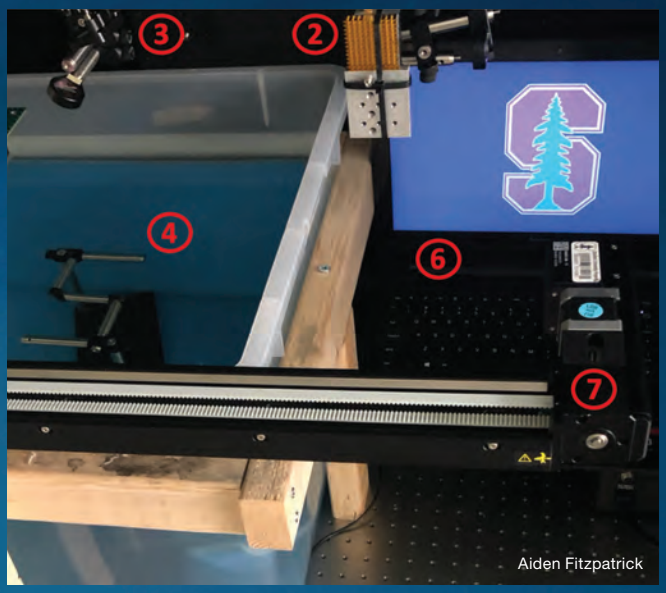
"If we can use light in the air, where light travels well, and sound in the water, where sound travels well, we can get the best of both worlds," said lead author Aidan Fitzpatrick, Ph.D. candidate in Electrical Engineering.

The system fires a laser from the air that gets absorbed at the water surface, then generates ultrasound waves that propagate down through the water and reflect off underwater objects before racing back. The signals are recorded and pieced back together into a 3D image of the submerged feature.

Fitzpatrick, A., Singhvi, A., & Arbabian, A. (2020). An Airborne Sonar System for Underwater Remote Sensing and Imaging. *IEEE Access, 8*, 189945–189959.

> Our vision for this technology is on-board a helicopter or drone. We expect the system to be able to fly at tens of meters above the water.
>
> *— Aidan Fitzpatrick, Ph.D. candidate in Electrical Engineering*


Kindea Labs



Aiden Fitzpatrick

Kelp Forests and Ocean Acidification

An interdisciplinary analysis of giant kelp in California's Monterey Bay evaluated its potential to reduce ocean acidification, an impact of climate change on marine ecosystems that stems from more carbon dioxide (CO_2) being absorbed by seawater.

The results show that near the ocean's surface, the water is slightly less acidic, suggesting the kelp canopy does reduce acidity. Yet, those effects did not extend to the ocean floor, where most acidification has occurred, impacting sensitive corals, urchins and shellfish.

Kelp is thought to be a potentially ameliorating species in part because of its fast growth which involves a large amount of photosynthesis that produces oxygen and removes CO_2. Set up at Stanford's Hopkins Marine Station, the researchers collected data offshore in a 300-foot-wide kelp forest. At night, when they expected to see more acidic water, the water was actually less acidic, possibly caused by the upwelling of acidic, low oxygen water during the day.

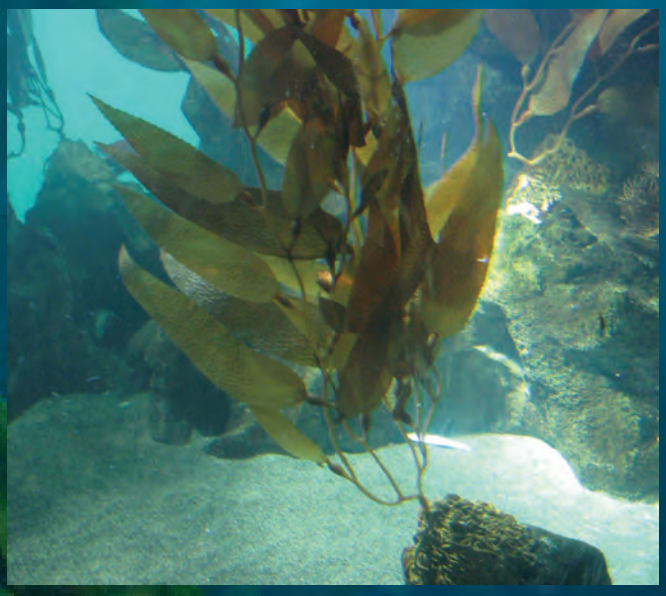
"It was wild to see the pH climb during the night when we were expecting increased acidity as a function of kelp respiration," said lead author Heidi Hirsh, Ph.D. candidate in Earth System Science. "One of the main takeaways for me is the limitation of the potential benefits from kelp productivity."

Although the kelp forests' mitigation potential didn't reach organisms on the sea floor, the kelp forest did create an overall less acidic environment and organisms are likely to benefit from this local acidification relief.

Hirsh, H. K., Nickols, K. J., Takeshita, Y., Traiger, S. B., Mucciarone, D. A., Monismith, S., & Dunbar, R. B. (2020). Drivers of Biogeochemical Variability in a Central California Kelp Forest: Implications for Local Amelioration of Ocean Acidification. *Journal of Geophysical Research: Oceans, 125*(11).

> The current knowledge set is pretty large, but it tends to be disciplinary – it's pretty rare bringing all these elements together to study a complex coastal system. In a way, our project was kind of a model for how a synthetic study pulling together many different fields could be done.
>
> *— Rob Dunbar, professor of Earth System Science*

Claire Fackler, CINMS, NOAA



Air Pollution Impact on Infant Mortality

A Stanford study of dust traveling thousands of miles from the Sahara Desert and birth outcomes in sub-Saharan Africa found that small increases in dust air pollution lead to large increases in infant mortality.

"Africa and other developing regions have made remarkable strides overall in improving child health in recent decades, but key negative outcomes such as infant mortality remain stubbornly high in some places," said senior author Marshall Burke, associate professor of Earth System Science.

Quantifying the health impacts of air pollution is challenging. To isolate the effects of air pollution exposure, the researchers analyzed 15 years of household surveys from 30 countries across Sub-Saharan Africa covering nearly 1 million births. Combining birth data with satellite-detected changes in particulate levels driven by dust from the Bodélé Depression in Chad provided a clearer picture of poor air quality's health impacts on children.

The researchers found a roughly 25% increase in local annual mean particulate concentrations in West Africa causes an 18% increase in infant mortality.

Emissions from natural sources could change dramatically in a changing climate. The researchers calculated a range of possibilities for sub-Saharan Africa that could be anywhere from a 13% decline in infant mortality to a 12% increase due to changes in rainfall over the desert.

As a solution, the researchers suggest deploying solar-powered irrigation systems in the Bodélé region to stop dust from going airborne, which could avert 37,000 infant deaths per year in West Africa at a cost of $24 per life, making it competitive with many leading health interventions.

Heft-Neal, S., Burney, J., Bendavid, E., Voss, K. K., & Burke, M. (2020). Dust pollution from the Sahara and African infant mortality. *Nature Sustainability, 3*(10), 863–871.

> While our calculation doesn't consider logistical constraints to project deployment, it highlights the possibility of a solution that targets natural pollution sources and yields enormous benefits at a modest cost.
>
> *— Sam Heft-Neal, research scholar at Stanford's Center on Food Security and the Environment*

George Steinmetz

Nick Brooks

Wolfgang Hasselmann

Enabling Prescribed Burns

Prescribed burns – fires set under controlled conditions to clear ground fuels – are effective at reducing wildfire risks, but perceived and real risks, regulations and resource shortages are barriers to their use. A Stanford study published in *Nature Sustainability* outlines a range of approaches to overcome these issues and enable more prescribed burns in California and potentially other regions, including Australia.

"We need a colossal expansion of fuel treatments," said lead author Rebecca Miller, a Ph.D. candidate in the Emmett Interdisciplinary Program in Environment and Resources.

Prescribed burns rarely escape their boundaries and have ecological benefits that mimic the effects of naturally occurring fires. To stem devastating wildfires, California needs fuel treatments on nearly 20% of the state's land. While private, state and federal acres planned for prescribed burns in California has increased, up to half of that acreage has gone unburned due to concerns about smoky air, outdated regulations and limited resources.

The researchers interviewed government employees, legislative staff, nonprofit representatives and academics involved with wildfire management and analyzed policies and prescribed burn data to identify barriers and propose solutions.

Interviewees described a risk-averse culture fearing bankruptcy, punishment, and negative public opinion regarding the use of prescribed burns. Limited finances, complex regulations and a lack of qualified burners were also deterrents.

Potential solutions include recent legislation making private landowners who enroll in a certification program before burning exempt from financial liability for escaped prescribed burns, public education programs improving public opinion, consistent funding for wildfire prevention, federal workforce rebuilding and training programs to bolster prescribed burn crews, and standardization of regional air boards' burn evaluation and approval processes.

Miller, R. K., Field, C. B., & Mach, K. J. (2020). Barriers and enablers for prescribed burns for wildfire management in California. *Nature Sustainability, 3*(2), 101–109.

> Prescribed burns are effective and safe. California needs to remove obstacles to their use so we can avoid more devastating wildfires.
>
> *— Chris Field, director of the Stanford Woods Institute for the Environment*

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Mark Mooney

Accessible Healthcare as Climate Solution

Affordable health care can help protect rainforests, slow climate change and create significant monetary value, according to a Stanford-led study published in *Proceedings of the National Academy of Sciences*. The researchers found that deforestation in Indonesia's Gunung Palung National Park declined 70% in a decade after a clinic opened. The clinic, which accepts bartering and gives discounts based on logging reductions, could serve as a model for preserving carbon sinks while reversing poverty and negative health outcomes.

"Health and climate can and should be addressed in unison, and done in coordination with and respect for local communities," said study co-author Michele Barry, senior associate dean of Global Health.

Though tropical forests are crucial carbon reservoirs vital to slowing climate change and mass extinction, they are being deforested at alarming rates. Economic hardship can lead local communities with few alternatives to illegal logging. Lack of affordable healthcare can compound the problem, continuing cycles of poor health and high costs.

Researchers worked with two non-profits that established a healthcare clinic adjacent to the park serving thousands of patients. Analyzing clinic records with satellite observations of forest cover, they found declines in diseases, such as malaria, coupled with declines in deforestation.

"We didn't know what to expect when we started evaluating the program's health and conservation impacts, but were continually amazed that the data suggested such a strong link between improvements in health care access and tropical forest conservation," said lead author Isabel Jones, recent recipient of a Ph.D. in Biology.

The greatest drop-offs in logging occurred adjacent to villages with the highest rates of clinic usage.

Jones, I. J., MacDonald, A. J., Hopkins, S. R., Lund, A. J., Liu, Z. Y. C., Fawzi, N. I., Purba, M. P., Fankhauser, K., Chamberlin, A. J., Nirmala, M., Blundell, A. G., Emerson, A., Jennings, J., Gaffikin, L., Barry, M., Lopez-Carr, D., Webb, K., de Leo, G. A., & Sokolow, S. H. (2020). Improving rural health care reduces illegal logging and conserves carbon in a tropical forest. *Proceedings of the National* Academy of Sciences of the United States of America, 117(45), 28515–28524.

> This is a case study of how to design, implement and evaluate a planetary health intervention that addresses human health and the health of rainforests on which our health depends.
>
> *— Susanne Sokolow, senior research scientist at the Stanford Woods Institute for the Environment*

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Drone Surveys of Antarctic Penguin Colonies

In order to document a colony of about 1 million Adélie penguins in Antarctica, Stanford engineers devised a path-planning algorithm enabling an autonomous multi-drone imaging system to perform aerial surveys. The study, published in *Science Robotics*, produced detailed visual surveys of about 300,000 nesting pairs of Adélie penguins over a 2-square-kilometer area at Cape Crozier and a smaller colony of about 3,000 nesting pairs at Cape Royds. Previous surveys took two days, whereas the new technique took roughly 2.5 hours due to the route planning algorithm coordinating two to four autonomous drones and prioritizing efficient colony coverage.

"Just moving all of that equipment down to a remote site and being able to prepare it, field it and deploy it with nothing other than tents and a small warming hut at your disposal, that's really phenomenal," said senior author Mac Schwager, assistant professor of Aeronautics and Astronautics, who spent months in Antarctica for the project.

Biologists need surveys to study penguin population size, birth rates and nesting density. Traditional surveys are constrained by costs, time efficiency and risk of disturbing the birds. Overcoming these challenges, the team's algorithm assigns destination points to each drone and figures out how to move the drones in the most efficient way, saving time and lowering costs.

Parker Levinson

Kunal Shah

Liam Quinn

"The process was quick. What had been just the algorithm's squiggles on a screen the day before turned into a massive image of all the penguins in the colonies," said lead author Kunal Shah, Ph.D. candidate in Mechanical Engineering.

The team envisions other uses for the multi-drone system, such as tracking wildfires.

Shah, K., Ballard, G., Schmidt, A., & Schwager, M. (2020). Multidrone aerial surveys of penguin colonies in Antarctica. Science *Robotics, 5*(47), 3000.

> Humans could never leap into the sky and count 300,000 penguins or track a forest fire. I think that teams of autonomous robots can really be powerful in helping us manage our changing world, our changing environment, at a scale that we never could before.
>
> *— Mac Schwager, assistant professor of Aeronautics and Astronautics*

Parker Levinson

Tracking Gravity Waves

Using data from giant superpressure balloons designed to provide internet service, Stanford researchers have gained a better understanding of gravity waves, tiny atmospheric ripples that can interact with the jet stream, polar vortex and other phenomena. The data was provided by Loon LLC, which sends thousands of sensor-laden balloons 12 miles up in the stratosphere for 100 days or more.

"This was just a very lucky thing because they weren't collecting data for any scientific mission. But, incidentally, they happened to be measuring position and temperature and pressure," said senior author Aditi Sheshadri, assistant professor of Earth System Science.

Gravity waves emerge when blobs of air are forced upward and then pulled down by gravity and can travel thousands of miles, carrying momentum and heat along with them. Understanding them is key to improving weather forecasts and climate models.

"They help to drive the overall circulation of the atmosphere, but some gravity waves are too small and too frequent to be observed with satellites," said lead author Erik Lindgren, a postdoctoral scholar in Earth System Science at the time of the study.

"Getting gravity waves right would help constrain circulation responses to climate change, like how much it's going to rain in a particular location, the number of storms – dynamical things such as wind and rain and snow," Sheshadri said.

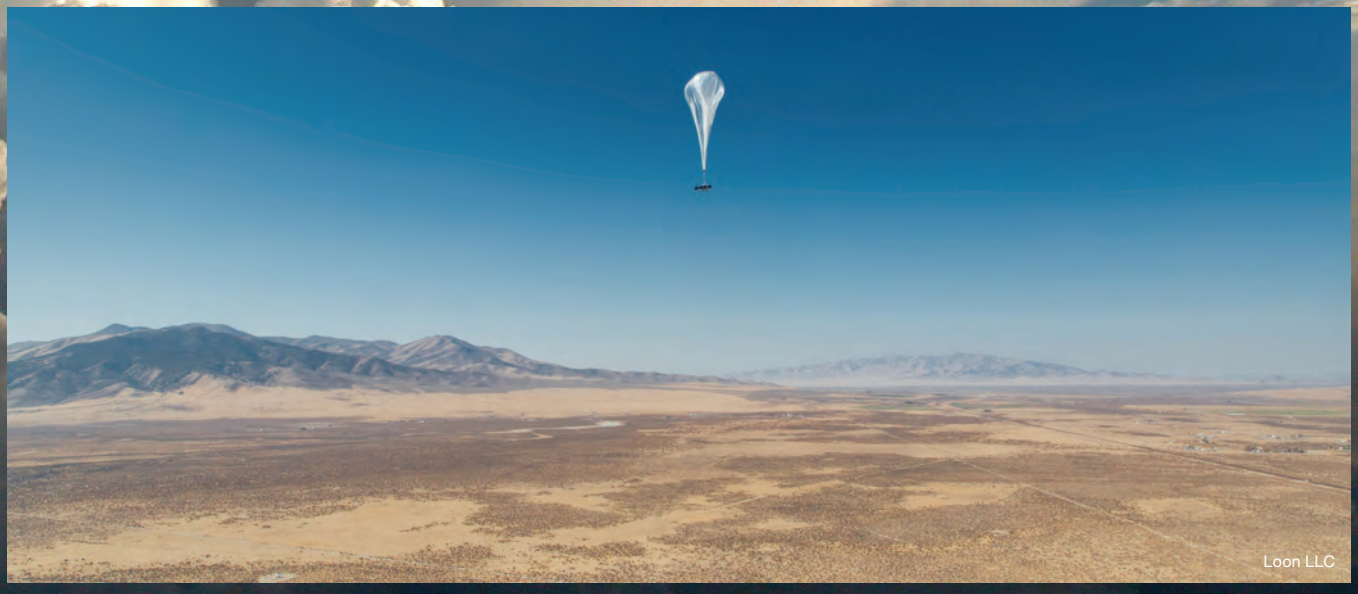

Loon LLC


Loon LLC

Calculating gravity wave motions from data from 2014 to 2018, the researchers focused on energy associated with high-frequency gravity waves at different time scales, and how it varies across seasons and latitudes. They found in summer, the waves are larger and build up more kinetic energy in the tropics, and in winter, smaller waves moving with less energy are more common close to the poles.

> Until now, it has not been entirely clear how these waves behave in different regions or over the seasons at very high frequencies or small scales.
>
> *— Erik Lindgren, postdoctoral scholar in Earth System Science*

Lindgren, E. A., Sheshadri, A., Podglajen, A., & Carver, R. W. (2020). Seasonal and Latitudinal Variability of the Gravity Wave Spectrum in the Lower Stratosphere. *Journal of Geophysical Research: Atmospheres, 125*(18).



Loon LLC

Desalination Solution

Stanford researchers have created a device that could make converting seawater to freshwater profitable and environmentally benign. Published in *ACS Sustainable Chemistry & Engineering*, the study outlines an efficient method for transforming brine into commercially valuable chemicals as part of the desalination process. The approach avoids the need for disposing potentially hazardous chemicals in local ecosystems.

"Desalination could be a powerful tool to mitigate water scarcity around the world, but it is limited by energetic and monetary costs for treatment and brine management," said senior author Will Tarpeh, assistant professor of Chemical Engineering. "By reimagining brine as a resource, we aim to incentivize its collection and treatment before discharge."

Desalination plants produce about 27 billion gallons of drinking water worldwide each day. However, converting saltwater to potable water is costly, requiring a lot of energy, and produces about 1.5 times more brine than potable water.

The researchers designed a device that splits the components of brine through electrochemical water-salt splitting. Water-salt splitting separates the brine into positively charged sodium and negatively charged chlorine ions with the use of an electrochemical cell. Once the bonds are broken, sodium and chlorine combine with other elements to form new chemicals including sodium hydroxide, hydrogen and hydrochloric acid.

Many products including paper and soap use sodium hydroxide, also known as lye, in their manufacturing. Hydrogen is used for industrial purposes such as fertilizer production. Hydrochloric acid is used as a component in battery production and other uses.

Mu, L., Wang, Y., & Tarpeh, W. A. (2020). Validation and Mechanism of a Low-Cost Graphite Carbon Electrode for Electrochemical Brine Valorization. *ACS Sustainable Chemistry and Engineering, 8*(23), 8648–8654.

Montgomery County Planning Commission

James Grellier

> Our research was able to identify a design that not only costs less but also outperforms conventional water-splitting methods.
>
> *— Linchao Mu, postdoctoral research fellow in Chemical Engineering*

> Ultimately, this exemplifies our vision to design water treatment that recovers valuable products from 'waste' streams using selective separations.
>
> *— Will Tarpeh, assistant professor of Chemical Engineering*

Flood Risk in the Western U.S.

Flood sizes increase exponentially as a higher fraction of precipitation falls as rain, according to a Stanford study that analyzed more than two decades of data in the western U.S. The findings offer insight into how flood risks may change as warming increases and there is less snow.

Looking at over 400 watersheds from 1980 to 2016, the researchers found that winter floods driven by rainfall can be more than 2.5 times as large as those driven by snowmelt. Moreover, the size of floods increased at a faster rate than the increase in rain.

"These results show that warming alone – even without changes in precipitation amounts – could lead to changes in the size of floods," said lead author Frances Davenport, Ph.D. candidate in Earth System Science.

The results could inform management of reservoirs that secure the region's water supply and provide a buffer for flooding. "Both the shape and magnitude of our non-linear results have the potential to benefit planners in Western states that are trying to integrate the changing nature of snow hydrology into their decisions," said senior author Noah Diffenbaugh, professor of Earth System Science.

Collaborating with Marshall Burke, associate professor of Earth System Science, the researchers adapted methods from econometrics to account for other influences like soil characteristics, in order to show the impact of precipitation alone.

The study focused on the western U.S. because the dams and reservoirs used to store water for the dry season also provide flood control during the wet season, with snow playing an important role.

Davenport, F. V., Herrera-Estrada, J. E., Burke, M., & Diffenbaugh, N. S. (2020). Flood Size Increases Nonlinearly Across the Western United States in Response to Lower Snow-Precipitation Ratios. *Water Resources Research, 56*(1).

> States like California are well aware that as the snow hydrology of the western U.S. continues to change, the infrastructure that was designed and built around the old climate of the last century will continue to be pushed to its limits.
>
> *— Frances Davenport, Ph.D. candidate in Earth System Science*

Sean Davis

Petty Officer Jaclyn Young

Sergey Kochkarev

U.S. Coast Guard

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PUBLICATIONS

CLIMATE

Adger, W. N., Crépin, A.-S., Folke, C., Ospina, D., Chapin, F. S., Segerson, K., Seto, K. C., Anderies, J. M., Barrett, S., Bennett, E. M., Daily, G., Elmqvist, T., Fischer, J., Kautsky, N., Levin, S. A., Shogren, J. F., van den Bergh, J., Walker, B., & Wilen, J. (2020). Urbanization, Migration, and Adaptation to Climate Change. One Earth, 3(4). DOI: 10.1016/j.oneear.2020.09.016

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