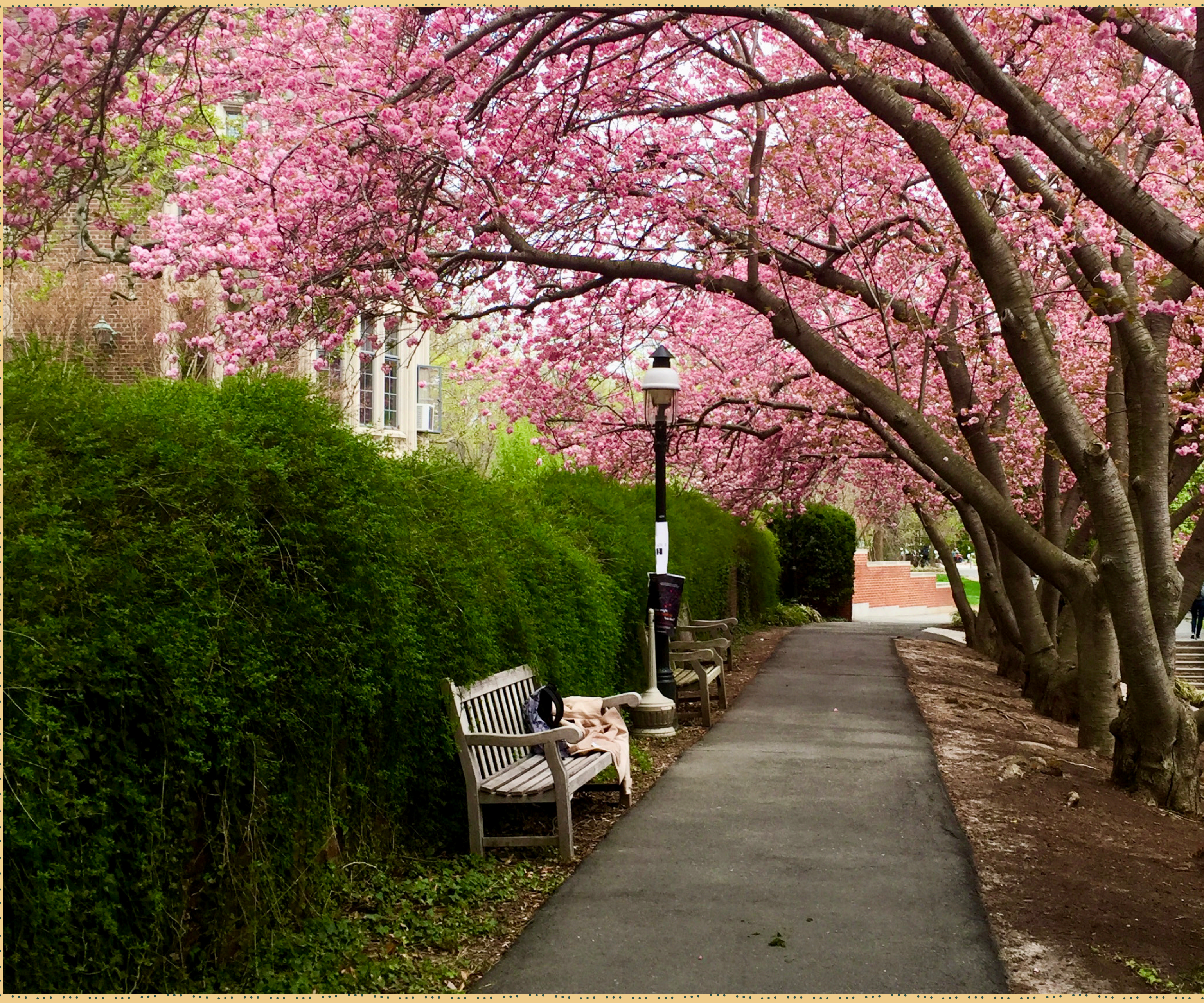
PRINCETON UNIVERSITY

Annual Report 2023 Executive Summary

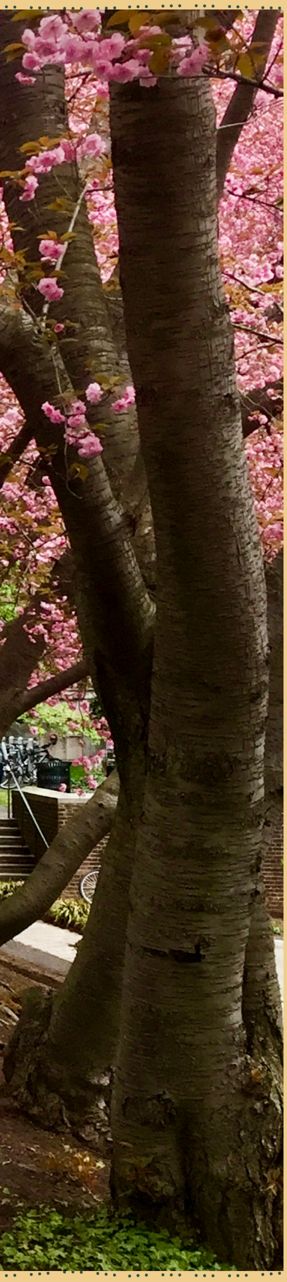
High Meadows Environmental Institute

Carbon Mitigation Initiative

Introduction



The Carbon Mitigation Initiative (CMI), administered by the High Meadows Environmental Institute (HMEI) at Princeton University, is a 24-year-old partnership with bp. CMI currently funds 21 principal investigators (PIs) and over 60 researchers and students. Teams of scientists, engineers, and policy experts are working across multiple disciplines to develop solutions to the world's biggest climate, carbon and biodiversity problems and to mitigate their impacts on societies around the globe. In this report, each of the PIs has selected one feature of their research from 2023 to highlight, summarize and provide context for their work. The research highlights are followed by a complete list of the year's peer-reviewed publications.



Ongoing Research Activities

The Inflation Reduction Act of 2022 is projected to fundamentally change carbon emissions of the United States. Princeton's Net-Zero America project provided substantial input into this legislation and the CMI continues to invest in activities that follow from the initial work. Jesse Jenkins' ZERO lab is developing a model called MACRO that would help governments around the world plan cost effective transitions to net-zero. The Greig group is focused on real-world barriers to carbon mitigation projects, including availability of development capital, community support, the need to train a new workforce and logistical constraints on deployment.

In 2023, CMI continued to explore options for new mitigation technologies. Researchers are looking for efficient and economical ways to produce and use hydrogen as a fossil fuel replacement, with ammonia being a major contender for its transport. In *PNAS*, CMI researchers, including members of the Porporato, Carter, Mueller and Zondlo groups, analyzed emissions from an ammonia economy. Eric Larson's group examined the potential for forest-based bioenergy projects in the southern United States. Claire White and her group focused on alternative cements that reduce emissions without sacrificing long-term performance.

CMI's Natural Climate Solutions (NCS) program investigates how land use can impact biodiversity and mitigate or offset carbon emissions. The partnership with University of California Santa Barbara's Environmental Market Solutions Lab (emLab) and the Environmental Defense Fund (EDF) explores, through a series of econometric analyses, how changes in land use respond to market incentives in different countries around the globe. The researchers, including principal investigators Kathy Baylis, Robert Heilmayr, and Andrew Plantinga, looked at how deforestation has responded in the past to changes in crop prices. Robert Pringle's group analyzed how large herbivores in the African savannas impact carbon stocks in that region, along with environmental and land-use changes. Jonathan Levine and members of his lab developed high-resolution maps of 19 different land-based strategies for mitigating climate change. These maps show locations where such strategies can best help balance the global carbon budget. The Zhang group identified the influence of environmental and soil conditions that predict methane emissions from wetlands.

CMI's 2023 research also examined how oceans and terrestrial vegetation interact with anthropogenic carbon in the atmosphere. This is important because terrestrial and oceanic carbon sinks are primary determinants of humanity's remaining budget for fossil fuel emissions. Laure Resplandy's work explored how oceans respond to decreased oxygen associated with climate change. The Pacala group worked on developing the first models that predict both the maintenance of biodiversity that affects carbon and hydrologic cycling and the impact of this biodiversity on climate. At GFDL, the Shevliakova group focused on improving Earth System Models to reduce uncertainty in the prediction and projections of land carbon stocks. The Vecchi lab improved their modeling of tropical cyclones using reconstruction from sedimentary paleohurricane records with the goal of better understanding hurricane activity.

Best Paper Awards 2023

Since 2010, the CMI Best Paper Award for Postdoctoral Fellows has been presented annually to one or two CMI-affiliated postdoctoral research associate(s) or research scholar(s) selected for their contribution to an important CMI paper. In late 2019, CMI created a similar award honoring a CMI-affiliated doctoral student for their contributions to an important CMI paper.

Matteo Bertagni, Postdoctoral Research Associate at HMEI, received the Robert H. Socolow Best Paper Award for Postdoctoral Fellows for his work on the paper "Risk of the hydrogen economy for atmospheric methane," published in *Nature Communications*. The third Robert H. Socolow Best Paper Award for Doctoral Students was given to Wilson Ricks, who is a PhD student in the Jenkins lab. He received the award for his work on the paper "Minimizing emissions from grid-based hydrogen production in the United States," published in *Environmental Research Letters*.

Matteo Bertagni (left), winner of the 2022 Best Paper Award for Postdoctoral Fellows.
Wilson Ricks (right), winner of the 2022 Best Paper Award for Graduate Students.

Awards and Honors

In 2023, Professor Emily Carter, Gerhard R. Andlinger Professor in Energy and the Environment, Professor of Mechanical and Aerospace Engineering, and Senior Strategic Advisor and Associate Laboratory Director for Applied Materials and Sustainability Sciences at the Princeton Plasma Physics Laboratory, was honored with the William H. Nichols Medal for 2024, a prestigious annual honor bestowed by the American Chemical Society's (ACS) New York Section for outstanding contributions in chemistry. The Section chose Carter for "groundbreaking quantum insights in sustainable catalysis" (source: https://www.pppl.gov/news/2023/carter-honored-2024-william-h-nichols-medalist).

In 2023, Jesse Jenkins, Assistant Professor of Mechanical and Aerospace Engineering and the Andlinger Center for Energy and the Environment, was awarded Engineering News Record top 25 Newsmakers of 2022 for "predicting and understanding climate-change impacts now and in the future, and in leading efforts to model how solutions might work and how to get them done" (source: https://www.enr.com/articles/55792-jesse-d-jenkins-princeton-professor-leads-team-modeling-how-2022-law-can-propel-us-action-on-climate-change).

Michael Mueller, Professor of Mechanical and Aerospace Engineering, was elected a Fellow of the American Society of Mechanical Engineers (source: https://mae.princeton.edu/about-mae/news/michael-e-mueller-elected-fellow-american-society-mechanical-engineers).

(From left to right)
Emily Carter,
Jesse Jenkins and
Michael Mueller



Gabriel Vecchi, Knox Taylor Professor of Geosciences and HMEI and Director of HMEI, was selected as a 2024 American Meteorological Society Fellow. The AMS recognizes outstanding leaders in the weather, water, and climate communities at their annual meetings. The society's mission is to advance atmospheric and related sciences, technologies, applications, and services by supporting climate science experts and organizations (source: https://vecchi.princeton.edu/news/prof-gabriel-vecchi-has-been-selected-2024-american-meteorological-society-fellow).

In January 2024, Claire White, Associate Professor of Civil and Environmental Engineering and the Andlinger Center for Energy and the Environment, was awarded $3 million from the U.S. Department of Energy (DOE) to lead the interdisciplinary effort on the decarbonization of concrete. She will lead a consortium of researchers and practitioners from academia on "Inter-grinding of Waste Activators and Low-grade Calcined Kaolin Clay for One-part Alkali-activated Concrete Technology" (source: https://cee.princeton.edu/news/professor-claire-white-has-been-awarded-3000000-january-us-department-energy-doe). White was also one of just four faculty to receive the 2023 President's Award for Distinguished Teaching at Princeton.

Gabriel Vecchi (left) and *Claire White* (right)

Research – At a Glance

Minimizing Reactive Nitrogen Emissions From Ammonia Energy

INVESTIGATORS: MATTEO BERTAGNI, EMILY CARTER, CHRIS GREIG, YIGUANG JU, TIM LIEUWEN, JOHN MARK MARTIREZ, MICHAEL MUELLER, AMILCARE PORPORATO, ROBERT SOCOLOW, SANKARAN SUNDARESAN, RUI WANG AND MARK ZONDLO

Ammonia (NH_3) is an attractive solution to transport and store hydrogen (H_2). The fertilizer industry has developed a mature and robust ammonia infrastructure over the last century, H_2 conversion to NH_3 has a low energy penalty, and ammonia can either be converted back to H_2 through cracking or burned as a low-carbon fuel. However, ammonia energy adoption nonetheless faces challenges. The potential emission of reactive nitrogen species (NH_3, NO_x, and N_2O) negatively impacts air quality, the environment, human health, and climate. In a multidisciplinary effort, Porporato's research group and collaborators have quantified these potential emissions from worst-to-best-case scenarios. This work highlights the need for proactive engineering practices and policies to reduce environmental concerns.

The CMI Wetland Project: Understanding the Biogeochemical Controls on Wetland Methane Emissions for Improved Climate Prediction and Methane Mitigation

INVESTIGATORS: XINNING ZHANG AND LINTA REJI

Methane (CH_4) is the second most important anthropogenic climate forcer after carbon dioxide. Determining the importance and mechanisms of different anthropogenic and natural methane sources and sinks across temporal and spatial scales remains a fundamental challenge for the scientific community. Wetlands are dominant but highly variable sources of methane and are predicted to play a critical role in carbon-climate feedbacks. Methane emissions from these areas are shaped by a complex and poorly understood interplay of microbial, hydrological, and plant-associated processes that vary in time and space. The factors responsible for the greatest methane emission from wetlands remain unknown. The CMI Wetland Project aims to identify the biological and chemical mechanisms that promote methane emissions from wetlands. The goal is to improve predictions of carbon-climate feedbacks and strategies of methane mitigation. A better understanding of the factors responsible for the greatest methane emission from wetlands is crucial to bp's actions aimed at targeting this powerful greenhouse gas and thus a vital step towards a low-emissions future.

Mapping Opportunities for Land-Based Climate Mitigation

PRINCIPAL INVESTIGATOR: JONATHAN LEVINE

Reaching net-zero emissions in the current century entails a massive deployment of various land use and land management practices aimed at reducing carbon emissions and increasing carbon sequestration. These strategies range from avoiding deforestation and restoring carbon dense ecosystems, to more technical solutions such as enhanced chemical weathering and bioenergy with carbon capture and storage. To explore the options and opportunity costs resulting from scaling up land- and nature-based climate mitigation, Jonathan Levine's group derived global, high-resolution maps of 19 different strategies for mitigating climate change. These maps provide opportunities for how and where land-based mitigation can positively contribute to global efforts to reduce climate change.

Understanding How Economic Incentives Influence Land-Use Decisions

PRINCIPAL INVESTIGATORS: KATHY BAYLIS, ROBERT HEILMAYR AND ANDREW PLANTINGA

To help reach climate goals, policymakers and practitioners around the world are exploring programs that incentivize people to make land-use decisions that reduce net greenhouse gas emissions. These decisions include avoiding deforestation, practicing climate-smart agriculture, or pursuing ecological restoration. The Environmental Markets Lab (emLab) at the University of California, Santa Barbara (UCSB) is conducting econometric analyses to understand and evaluate the effectiveness of these incentives on a national and global scale. The goal is to explore how responsive land-use decisions are to financial incentives, and the political, cultural, and economic factors that influence these responses. Research findings will help policymakers understand the potential impact that incentives for land-based climate solutions and policy design could have on land use and associated emissions.

Quantifying the Carbon Footprints of the World's Largest Mammals

PRINCIPAL INVESTIGATOR: ROBERT PRINGLE

The last five years have brought growing recognition of the role of animals in the global carbon cycle, along with optimistic projections about the possibility of synergies between biodiversity conservation and carbon storage. African savannas are home to the world's greatest diversity of large mammals and are also considered attractive habitats for carbon offsets, because savannas can vary more than tenfold in vegetation biomass and can in theory be induced to switch between low-carbon and high-carbon states. Yet, savanna carbon storage, and hence the viability and sustainability of offset projects, depend on the interplay between herbivory, fire, and rainfall—and these interdependencies are not yet understood. Robert Pringle's research group is using remote sensing and field experiments to understand how elephants and other large herbivores influence above- and below-ground carbon stocks in conjunction with broader environmental and land-use changes.

Assessing Carbon Emission Impacts of Forest-Based Bioenergy

PRINCIPAL INVESTIGATOR: ERIC LARSON

Researchers in Eric Larson's group have developed a framework for assessing the dynamic lifecycle greenhouse gas impacts of hypothetical forest-based bioenergy projects and applied it to case studies involving utilization of feedstocks from forest basins in the southern U.S. Understanding the carbon impacts of using woody feedstocks from this region (called the "wood basket of the country") is important to ensure that such projects are climate friendly.

MACRO: A New, High-Performance, Electricity-Centric Model to Understand Paths to Net-Zero

PRINCIPAL INVESTIGATOR: JESSE JENKINS

Princeton's ZERO Lab, led by Jesse Jenkins, is developing a new open-source, high-performance macro-energy systems planning model to explore decarbonization technologies and chart cost-effective pathways to net-zero greenhouse gas emissions for countries around the world. The model leverages mathematical "decomposition methods" to take full advantage of parallel computing capabilities, delivering unprecedented resolution and improved co-optimization of increasingly coupled energy networks from electricity, liquid fuels and natural gas to hydrogen, bioenergy, and industrial processes.

Overcoming Challenges Facing the Execution of Net-Zero Energy Ambitions

PRINCIPAL INVESTIGATOR: CHRIS GREIG

A myriad of integrated assessment (IAM)- and macroscale energy system models continue to illustrate pathways to achieve deep decarbonization. Yet, most major economies remain far from achieving their net-zero emissions pledges. Questions about the feasibility of modeled pathways are becoming more prominent in the modeling community. However, most models lack the temporal granularity and sectoral interdependencies of investment decision-making, development, and construction required to address implementation feasibility. This research tries to bridge the gap between modeled scenarios and real-world characteristics and dynamics of investment decision-making, and infrastructure development and delivery.

Tropical Cyclones from Weather to Millennial Timescales

PRINCIPAL INVESTIGATOR: GABRIEL VECCHI

Over the last year, the Vecchi lab continued their efforts to understand the mechanisms behind tropical cyclone (TC) activity changes on timescales of years to decades. Tropical cyclones impact society and ecosystems through extreme wind, rain and surge. The Vecchi lab uses climate and atmospheric models, combined with analyses of the observed record, to help distinguish the extent to which observed multi-decadal to centennial changes in TC activity have been driven by large scale factors, such as ocean temperature changes, greenhouse gases, volcanic eruptions, or El Niño, as opposed to random atmospheric fluctuations. A better understanding of TC changes over time is key to building strategies to mitigate their damages for the public and private sectors.

Pore Structure and Permeability of Alkali-activated Metakaolin Cements with Reduced CO_2 Emissions

INVESTIGATORS: CLAIRE WHITE AND ANITA ZHANG

Portland cement is currently the most common type of cement used in concrete manufacture, but it is a significant source of atmospheric carbon dioxide (CO_2) due to the production process. To counter this, White and her group are developing sustainable cements that are alternatives to conventional Portland cement. These cements can reduce CO_2 emissions but with limited in-field evidence of proven long-term performance. By understanding the pore structures of these alternative cements, linking pore structure to permeability, and investigating the mechanism of effective additives, the researchers aim to create a predictive phenomenological model that can be used to identify the most suitable alternative cement for a specific environmental application. Reducing concrete emissions in the construction industry would have a large impact on CO_2 emissions, which aligns with bp's ambition of helping the world get to net-zero.

Climate Change and Suffocating Oceans

PRINCIPAL INVESTIGATOR: LAURE RESPLANDY

The Resplandy group's CMI research in the last year focused on the ocean response to climate change, in particular the loss of oxygen associated with climate change and how it influences ecosystems and ecosystem services, such as fisheries. The Resplandy group uses the latest generation of climate and ocean models to evaluate how ocean oxygen has evolved in the past and will evolve in the future. This is a key step in understanding and anticipating how greenhouse gas emissions will impact ecosystems. This work has led to two publications in the past year focusing on constraining drivers of global de-oxygenation and the fate of oxygen minimum zones (OMZs). Understanding the causes and mechanisms of reduced ocean oxygen in a warming world is important for energy industry policymakers, especially in helping them to make informed decisions about energy transition and mitigation.

Improving the Representation of Land-climate Interactions in the Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model ESM4.1

INVESTIGATORS: MAUREEN BEAUDOR, SERGEY MALYSHEV, CAIO MATTOS ROCHAS, ELENA SHEVLIAKOVA AND ENRICO ZORZETTO

The development of Earth System Models (ESMs) at major climate science centers around the world is intended to improve our capability to project climate changes caused by anthropogenic greenhouse gas emissions (GHGs). These models include interactions between the atmosphere, ocean, sea ice, and land. In addition, ESMs allow us to project how changes in the carbon uptake by the biosphere and terrestrial and marine sources may affect atmospheric concentrations of carbon dioxide and other GHGs. The overall goal is to better constrain mitigation pathways that would stabilize the climate.

Interaction Between Climate Change, the Carbon Cycle, and Biodiversity

PRINCIPAL INVESTIGATOR: STEPHEN PACALA

In 2023, the Pacala lab focused on the interaction between climate change, the carbon cycle and biodiversity. Decades of experimental and observational work has demonstrated strong relationships between terrestrial plant biodiversity and ecosystem-level carbon uptake, carbon storage and water cycling. Research has found that biodiversity impacts the pace and nature of climate change, and that climate change is a major threat to biodiversity. The two-way interaction between biodiversity and climate change implies feedback that could regulate or worsen climate change. The Pacala lab is working on the first models of this feedback. The intention is to include them in Earth System models that predict climate change. The goal is to develop a theory and models that simultaneously address the climate and biodiversity problems. In 2023 and over the last several years, the lab published models that show how species diversity is maintained in physiological and structural attributes of plants with important effects on the carbon and hydrologic cycles and climate. The researchers showed last year that all these models have the same unexpected underlying mechanism that maintains diversity, which will greatly facilitate the development of operational climate-biodiversity models. The lab also completed work on two worrisome carbon cycle feedback loops involving the proliferation of woody vines in tropical forests and bamboo takeover of forests in Asia. This research is important for companies and policy makers, as the overgrowth of these species could lead to rainforest collapse, which would greatly decrease humanity's remaining carbon budget.

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