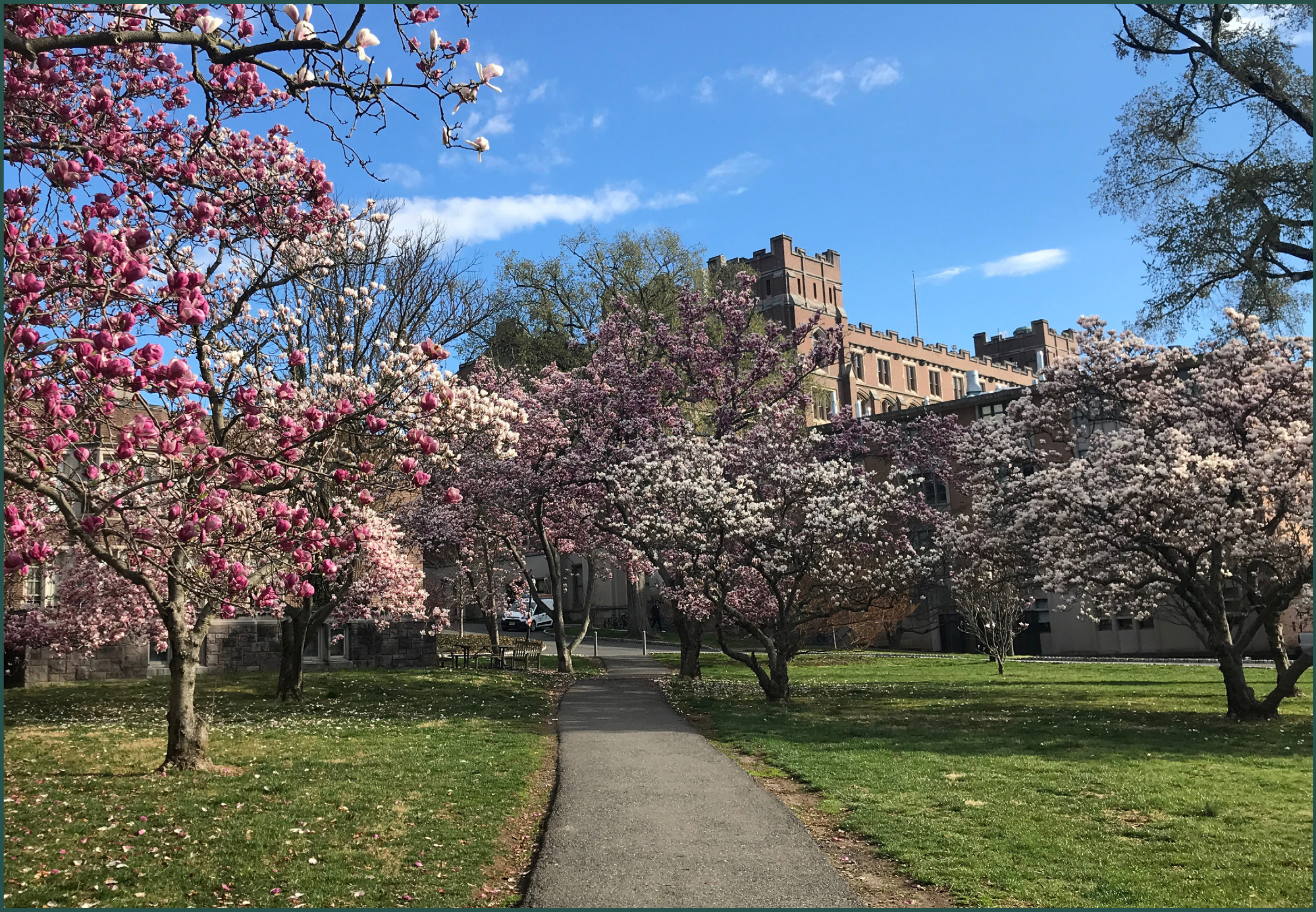
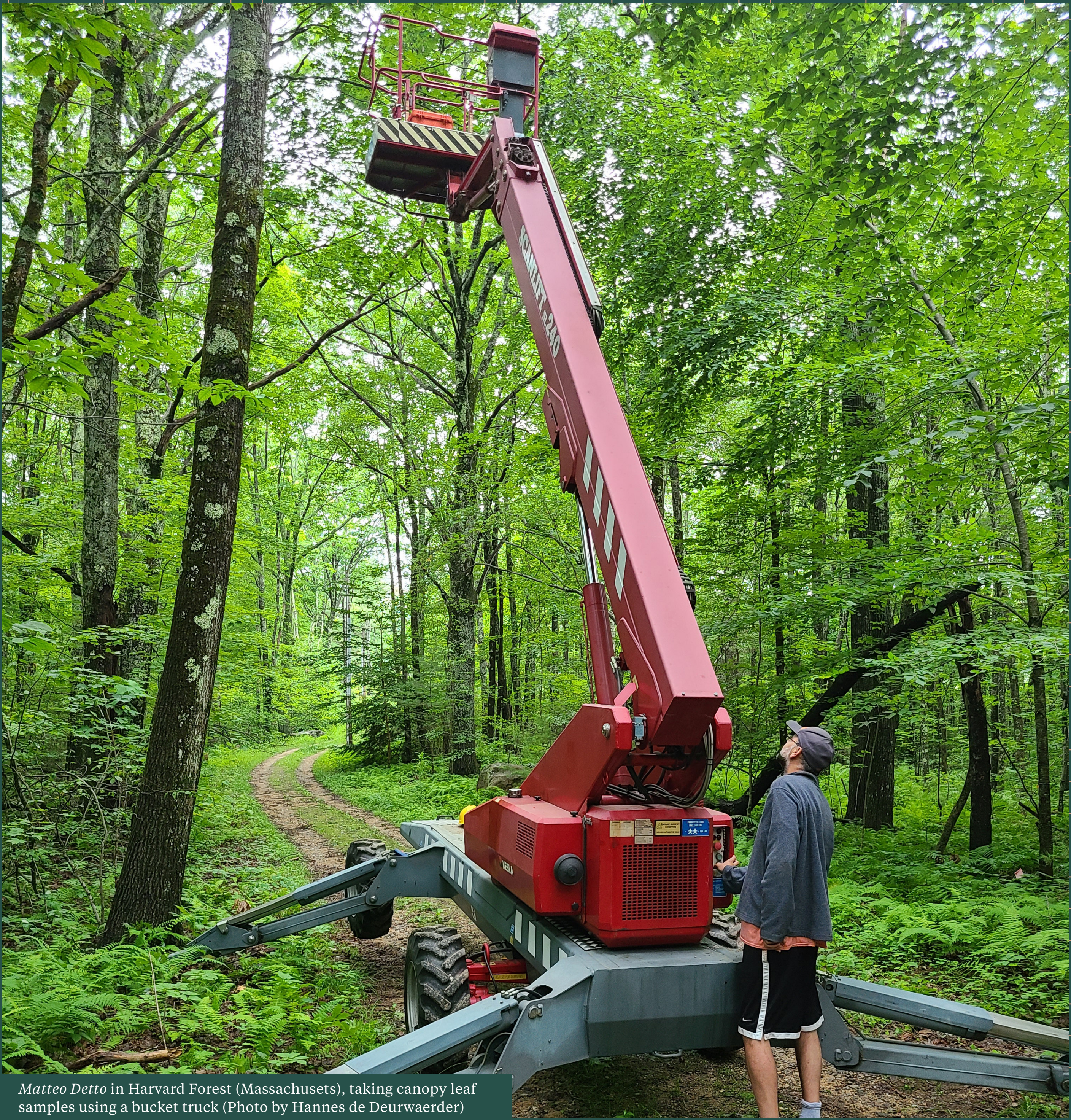
PRINCETON UNIVERSITY

Annual Report 2021 Executive Summary



High Meadows Environmental Institute

Carbon Mitigation Initiative

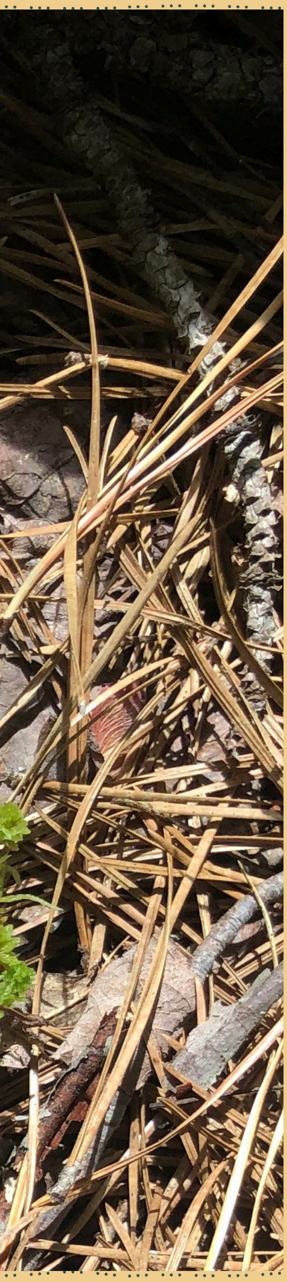


Matteo Detto in Harvard Forest (Massachusets), taking canopy leaf samples using a bucket truck (Photo by Hannes de Deurwaerder)

Cover
Eno Glade, Princeton University (Photo by Kristina Corvin)

Introduction

Peat from the Pine Barrens, New Jersey with American Tree Moss
(Photo by Linta Reji and Xinning Zhang)



The Carbon Mitigation Initiative (CMI) at Princeton University is the longest running partnership with industry in the university's history. Sponsored by bp and independently operated and administered by the High Meadows Environmental Institute (HMEI), CMI funds 15 principal investigators (PIs) and over 50 researchers who are tasked with finding compelling and sustainable solutions to the carbon and climate problems.

For 22 years, CMI has been leading the way in developing cutting-edge research in engineering, ecology, earth sciences, and environmental policy. This research has led to new insights into the impacts of climate change, developments in environmental engineering principles, and to salient policy recommendations and analyses that continue to impact the scientific and policy-making spheres, both domestically and internationally.

In this report, readers can find the latest information about CMI's key activities and research initiatives. Each of the fourteen highlights, written by CMI PIs and their teams, features a summary of the latest, on-going research conducted by their groups. The Highlights section is followed by a complete list of this year's CMI publications.

Ongoing Initiatives

Despite the COVID pandemic of the last two years, CMI researchers have maintained unabated research progress. One research initiative, which continues to gain traction globally and from which new projects were borne, The *Net-Zero America* project, has had outsized impact on policymakers and scientists in the US and abroad. Evolving from *Net-Zero America*, the REPEAT project allows policymakers and the public to view the impacts of proposed climate and energy policies before they are voted into law.

Another focus of CMI research in 2021 was carbon capture and storage (CCS), an important component in the transition to net-zero. Indeed, most models that show the economy achieving net-zero by 2050 rely heavily on this technology. CCS can be deployed by using hubs that carry CO_2 from various capture sites via pipeline networks to a centralized injection site. One 2021 CMI highlight posits that CCS will be limited by large-scale geologic limitations on the rate at which CO_2 can be injected. Another group of CMI researchers built a computer simulation tool to predict how geologic conditions can impact larger-scale geological carbon storage. Addressing the disconnect between CCS ambitions and constraints is crucial to successful CCS investment and policy decisions.

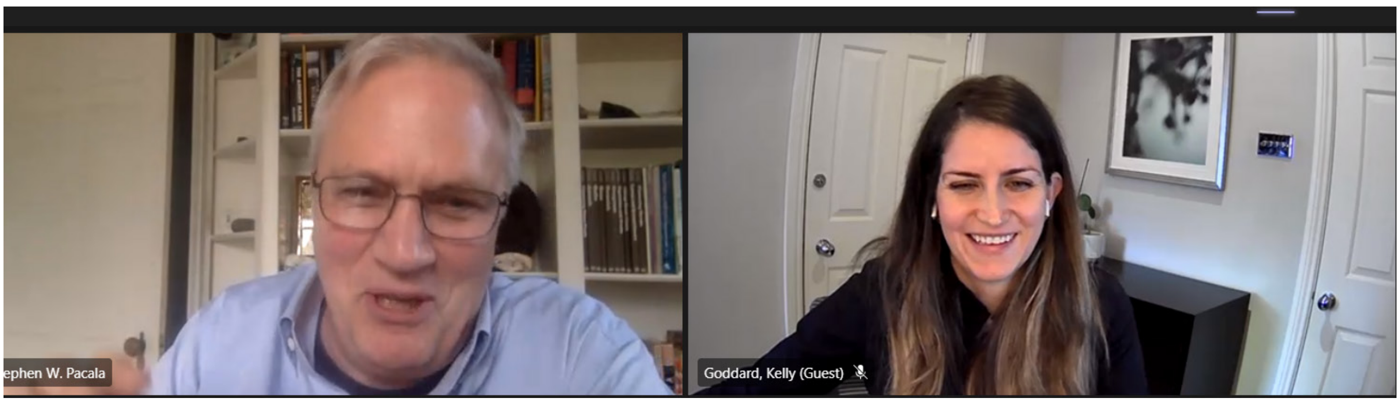
Other initiatives in the CMI research realm described in more detail in the following section include:

- Determining the impact of aerosol particles on global radiative forcing
- Consequences of hydrogen leakage on atmospheric methane
- Impacts of wetlands on methane emissions
- Predicting biodiversity responses to climate change
- Carbon capture through mineral-carbon interactions in water
- Using mathematical models to predict future climate
- Impacts of climate and fire on the fate of Amazonian forests
- Predicting reduced oxygen levels in the world's oceans
- Understanding the frequency of tropical cyclones
- Using calcium compounds for carbon capture

Annual Meeting

For the second consecutive year, the CMI Annual Meeting was held virtually in April 2021. Despite the lack of in-person interaction, the meeting allowed over 100 participants to come together from across the globe. The virtual program included several deep dives that explored a variety of energy and land-based climate solutions.

Speaking to over 100 attendees, Stephen Pacala, the Frederick D. Petrie Professor in Ecology and Evolutionary Biology and the Director of CMI opened the meeting stating, “There seems to be a recognition happening all at once in different parts of the world, in companies, board rooms, halls of government and the academy, that the transformation of our energy system to net-zero emissions of all greenhouse gases is feasible, economic and necessary.”



Stephen Pacala (left), the Director of the Carbon Mitigation Initiative (CMI), and *Kelly Goddard* (right), former Vice President for Carbon Ambition at bp and the bp executive sponsor of CMI, opened the 2021 CMI Annual Meeting held virtually on April 20-21.

During her welcoming remarks, Kelly Goddard, then Vice President for Carbon Ambition at bp and CMI’s bp executive sponsor remarked, “In early 2020, bp announced its ambition to become a net-zero company by 2050 or sooner, and to help the world get to net-zero. bp is now over one year on from announcing this ambition and we’re pleased that we have made progress against what we have planned. Societal expectations and calls for action continue to increase, reinforcing what we have set out and the need for collaboration to support action.”

“We continue to see our long-term collaboration with Princeton's CMI as an important science and technology partnership and we value the research being done by CMI to help the understanding of challenges and opportunities in the energy transition. Over the next two days, we will hear about the relevance of this research to bp and to broader stakeholders including policymakers,” said Goddard.

The meeting's first deep dive included speakers from the Biden Administration, non-governmental organizations, and bp who discussed the role of carbon capture utilization and sequestration (CCUS) in net-zero energy systems in the U.S., Australia, China, and Europe.

In another deep dive, CMI leadership team members and principal investigators, Jonathan Levine and Amilcare Porporato, described a newly launched CMI initiative aimed at determining how land-based climate solutions can be deployed globally to maximize carbon storage on land, while at the same time maintaining global biodiversity and food security.

"If we are going to actually achieve net-zero at a global level, country level or even a company level, land-based climate solutions must be deployed at massive spatial scales to have impact," said Levine.

In addition, Pacala announced the following recipients of two awards named in honor of Robert H. Socolow, Emeritus Professor of Mechanical and Aeronautical Engineering at Princeton and CMI Co-director from 2000 to 2019.

Best Paper Awards 2020

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.

Former Postdoctoral Researcher Erin Mayfield, now an assistant professor at Dartmouth College, received the Robert H. Socolow Best Paper Award for Postdoctoral Fellows for her work on the *Net-Zero America* report. The second Robert H. Socolow Best Paper Award for Doctoral Students was given to Ching Ho Justin Ng, who received his Ph.D. in Atmospheric and Oceanic Sciences from Princeton in 2019, for his paper "Large-scale environmental controls on the seasonal statistics of rapidly intensifying North Atlantic tropical cyclones," published in *Climate Dynamics*.

Erin Mayfield (left), a postdoctoral research associate in the High Meadows Environmental Institute received the Robert H. Socolow Best Paper award for the Postdoctoral Fellows. *Justin Ng*, who received his Ph.D. in Atmospheric and Oceanic Sciences from Princeton in 2019, was awarded the Robert H. Socolow Best Paper Award for Doctoral Students.

Collaborations

In addition to the external collaborations undertaken through the Princeton-led Net-Zero America project and the National Academies of Sciences, Engineering and Medicine Committee on Accelerating Decarbonization of the U.S. Energy System, CMI continued its engagement with three excellent research programs bp has long supported: the Center for the Environment at Harvard University; the Center for International Environment and Resource Policy at Tufts University; and the Thermal Engineering Department and the Tsinghua-bp Clean Energy Research and Educational Center at Tsinghua University.

New Collaborative Initiative

In 2021, CMI established a new initiative, *Land-Based Climate Solutions: Variable Responses to Economic Incentives*, in collaboration with University of California Santa Barbara and the Environmental Defense Fund. The project seeks to understand how economic, institutional, political, and cultural differences between countries are likely to affect the outcome of policy incentives encouraging private landowners to internalize climate impacts in their land-use decision making. The econometric analysis is expected to be completed in 2024.

Honors and Appointments

In 2021, CMI scholars were awarded with honors and appointments. Steve Pacala was appointed member of the President's Council of Advisors on Science and Technology (PCAST); Gabriel Vecchi was appointed Director of the High Meadows Environmental Institute; Laure Resplandy received an National Science Foundation Career Award to study the formation and future of Pacific and Indian Ocean dead zones; and Jesse Jenkins was awarded the Undergraduate and Graduate Engineering Council Award for Excellence in Teaching.

Research – At a Glance

Toward Accelerating the Deployment of CO_2 Capture and Storage Hubs

PRINCIPAL INVESTIGATOR: ERIC LARSON

Carbon dioxide (CO_2) capture and storage, including at bioenergy conversion facilities, will be crucial if the U.S. is going to reach net-zero emissions by 2050. The Energy Systems Analysis group launched new research in 2021 to explore with high spatial and temporal resolution how these features of the future energy landscape might evolve most expeditiously. The research attempts to understand the potential performance, benefits, costs, and challenges of deploying regional "hubs," which are clusters of CO_2 capture sites linked via pipeline networks to storage injection sites. A deep understanding of such hubs will help inform public and private decision-making to accelerate their deployment. An initial regional focus is the Louisiana Gulf Coast.

Bridging the Gap Between CCS Ambition and Reality

PRINCIPAL INVESTIGATOR: CHRIS GREIG

Most integrated assessment and other macro-scale energy system models find that widespread carbon capture and storage (CCS) at very large scales is crucial to achieve ambitious CO_2 reduction goals. However, these models assume that abundant low-cost geological storage is available to meet all needs. This research presents the contrasting view that storage capacity uncertainty could seriously hamper the pace and scale of CCS deployment, especially in developing Asian economies. This storage capacity uncertainty leads to "chicken-or-egg" challenges that deter investment. The implications for emissions reduction goals and the role that CCS should play in a net-zero future warrant more attention.

REPEAT Project Provides Real-time Look at Evolving U.S. Climate Policy

PRINCIPAL INVESTIGATOR: JESSE JENKINS

The REPEAT Project is led by Jesse Jenkins of the Princeton ZERO Lab. It provides a detailed, "real-time" evaluation of the United States' evolving energy and climate policies and the country's progress on the road to net-zero greenhouse gas emissions. The Project uses a novel suite of geospatially-granular planning, modeling, and visualization tools coupled with macro-scale optimization models of the United States energy system. The goal is to publish regular, timely, and independent environmental and economic evaluation of federal energy and climate policies as they are proposed and enacted. (See repeatproject.org.)

Nucleation and Growth of Nano-Aerosol Particles

PRINCIPAL INVESTIGATOR: IAN BOURG

The Bourg group is working to better understand the initial stages of nucleation and growth of secondary organic aerosol particles. Atomistic-level simulations reveal a strong affinity of organic molecules for the water-air interface and a previously unknown transition between two highly distinct structures during the initial stages of nano-aerosol particle growth. These particles, which spontaneously form in the atmosphere through clustering of water, natural or anthropogenic semi-volatile organics, and ions, are key unknowns in extant climate model predictions. Since the formation of these particles can be enhanced by land-use changes, their impact on climate must be considered in carbon mitigation strategies that modify carbon and water dynamics at the land-atmosphere interface.

Soil Uptake and Methane Feedback of Atmospheric Hydrogen

PRINCIPAL INVESTIGATOR: AMILCARE PORPORATO

Hydrogen (H_2) plays a crucial role in global energy scenarios aimed at achieving net-zero. Because it is not a greenhouse gas, H_2 has been touted as an alternative to fossil fuels in certain energy sectors. But the environmental consequences of perturbing the global hydrogen cycle are still largely unknown. Specifically, there are concerns around hydrogen interference with the methane (CH_4) atmospheric sink by the hydroxyl radical (OH). To sharpen future H_2 projections, the Porporato group has been quantitively addressing the major sink of tropospheric H_2, namely the soil uptake by bacteria, and the methane feedback of H_2 fugitive emissions. This research informs bp's aims of developing the H_2 economy in a manner that minimizes adverse climate impacts.

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

PRINCIPAL INVESTIGATOR: XINNING ZHANG

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 CMI Wetland Project aims to identify the biological and chemical mechanisms that promote methane emissions from wetlands. The goals are to improve predictions of carbon-climate feedbacks and strategies of methane mitigation. A better understanding of the factors responsible for the greatest methane emissions 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.

Modeling Large-Scale CO_2 Injection in Highly Reactive Rocks

PRINCIPAL INVESTIGATOR: MICHAEL CELIA

When carbon dioxide (CO_2) is injected into highly reactive rocks like basalts, the injected CO_2 will react quickly to form new carbonate rock. This is the most stable form of geological carbon storage. The Celia group built a computer simulation tool to study this process across a range of spatial scales. Small-scale injections show fast reaction rates, on the order of months to years that are consistent with results from small-scale field experiments. However, at the large spatial scales associated with practical industrial-scale injections, large-scale mass transfer limitations lead to much longer time scales for the reactions to proceed, on the order of a century or more. The newly developed computational tool allows these and other issues to be investigated efficiently. Progress in modeling and reliably assessing the potential of carbon sequestration in deep geological formations can help accelerate bp's efforts in decarbonizing heavy industry, while seeking new energy solutions.

Improving Forecasts of How Biodiversity Responds to Climate Change

PRINCIPAL INVESTIGATOR: JONATHAN LEVINE

To accurately assess the biodiversity benefits of slowing climate change through land-based climate solutions, the Levine group is challenging key mathematical assumptions in the leading biogeographic modeling tools for forecasting biodiversity response to climate and developing solutions critical for their accurate implementation. Reliably gauging the impact of mitigation initiatives on biodiversity is vital to current bp efforts towards a sustainable energy world.

The Efficiency of Enhanced Weathering

PRINCIPAL INVESTIGATOR: AMILCARE PORPORATO

Enhanced weathering (EW) is a negative-emission technology that holds the potential of alleviating the acidification of soils and natural waters. It is a carbon capture process designed to enhance and accelerate the chemical weathering of natural minerals that, when dissolved, remove carbon dioxide (CO_2) from the atmosphere and store it in natural waters. However, because the precise characterization of EW efficiency is still little understood, Porporato's research group has been working on quantifying the Alkalinization Carbon Capture Efficiency (ACCE) of any mineral dissolution in various natural waters. The findings provide an important step forward in the identification of suitable environmental conditions for EW applications, better quantification of EW carbon sequestration potential, and important context for bp's plans for natural climate solutions.

Pacala Group

PRINCIPAL INVESTIGATOR: STEPHEN PACALA

The Pacala group's CMI research in the last year has embraced a large number of topics, including the final report of the Princeton *Net-Zero America* project. The group also produced or co-produced a series of papers, including: (1) a paper on possible failure modes of President Biden's U.S. decarbonization agenda; (2) a paper on the need for separate national targets for CO_2 and methane emissions; (3) two papers (one in *Science*) on how fire and other disturbances work against land-based climate solutions); and (4) multiple papers (one in *Science*) that improve the capacity of climate models to represent the carbon cycle in tropical forests and other ecosystems. Although not directly supported by CMI, Stephen Pacala chaired the effort of the National Academies of Science, Engineering, and Medicine that produced a peer-reviewed policy manual for a U.S. transition to a net-zero economy, which extensively used the *Net-Zero America* report and was a primary reason that CMI initiated the *Net-Zero America* effort in the first place.

Future Fires Compromise Amazon Forest Resilience to Climate Change

PRINCIPAL INVESTIGATOR: ELENA SHEVLIAKOVA

Assessments of alternative mitigation strategies to limit the impact of global change increasingly rely on simulations of Earth System Models (ESMs). In the tropics, a major biodiversity refuge and a net sink for anthropogenic carbon dioxide (CO_2) emissions, ESMs consistently project that forests will thrive through the century due to CO_2 fertilization. In contrast, ecological models warn about a potential catastrophic forest loss under future drying conditions. A team of CMI researchers from the Pacala group and NOAA-GFDL used a state-of-the-art ESM to assess the impact of global change on tropical forest dynamics under alternative emission scenarios. Their ESM accounts, for the first time, for complex ecological mechanisms and large-scale biophysical forcing of vegetation dynamics. This research has broad consequences for the monitoring and management of tropical forests and opens new avenues for the design and implementation of carbon mitigation strategies. Of particular relevance to bp's natural climate solutions initiatives, this work informs the stability of carbon mitigated through avoided deforestation in tropical regions.

Diverging Fate of Oceanic Oxygen Minimum Zone and Its Core Under Global Warming

PRINCIPAL INVESTIGATOR: LAURE RESPLANDY

Global warming and anthropogenic activities are contributing to a loss of oxygen in the world's oceans. However, it is still unknown if this systematic deoxygenation will expand oxygen minimum zones (OMZs). These are areas where low oxygen levels threaten marine life and perturb the carbon and nitrogen cycles, potentially acting as an amplifying feedback on climate change. The Resplandy group uses the latest generation of climate model projections to evaluate how OMZs will evolve in the future, a key step to anticipate impacts on ecosystems, ecosystem services (e.g., fisheries), and greenhouse gas emissions. This work increases our understanding of an important oceanic impact of climate change that had many in the scientific community profoundly worried. It shows that, while serious, expanding oceanic dead zones do not represent the kind of tipping point that might significantly alter bp's plans for the energy transition.

Understanding Tropical Cyclone Frequency

PRINCIPAL INVESTIGATOR: GABRIEL VECCHI

The objective of this research from the Vecchi group is to better understand all aspects and variations in the statistics of tropical cyclone (TC) activity and other climate impacts over the past few centuries, as well as the coming one. An equally salient objective is to better understand the likely range of equilibrium and transient climate sensitivity, such as how much warming to expect from a doubling of atmospheric CO_2. Key tools in these studies are climate and atmospheric models. These, along with analyses of the observed record, help researchers to distinguish whether 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 the El Niño, as opposed to random atmospheric fluctuations.

Calcium (Ca)-Based Solid Sorbents for Low Temperature CO_2 Capture

PRINCIPAL INVESTIGATOR: CLAIRE WHITE

White and her group are developing novel calcium (Ca)-based solid sorbents that are capable of selectively capturing carbon dioxide (CO_2) from a mixed gas stream, or air, at ambient temperature. By understanding the solution chemistry during synthesis, the researchers have obtained phase pure Ca-based layered double hydroxides and demonstrated that these sorbents can selectively adsorb CO_2. Ongoing efforts are focused on engineering energy-efficient regeneration methods and quantifying life cycle environmental and economic aspects. This project aligns with bp's goal of developing solutions to decarbonize the cement production process, thereby helping cities and corporations to decarbonize.

Acknowledgments

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Carbon Mitigation Initiative Leadership and Administration
Stephen W. Pacala, director
Jonathan Levine, leadership team
Amilcare Porporato, leadership team
Kristina Corvin, administrator

Rajeshri D. Chokshi, technical support specialist
Stacey T. Christian, business administration
Katharine B. Hackett, executive director, High Meadows Environmental Institute
Michelle Link, program assistant
Hans Marcelino, web developer
Mae-Yung Tang, assistant web developer

Contributing Editors
Kristina Corvin
Thomas Garlinghouse

For more information, visit us at CMI's website – cmi.princeton.edu – or email us at cmi@princeton.edu.

High Meadows Environmental Institute

Carbon Mitigation Initiative

bp

Guyot Hall, Room 129
Princeton University
Princeton, New Jersey 08544

(609) 258-3832
cmi@princeton.edu