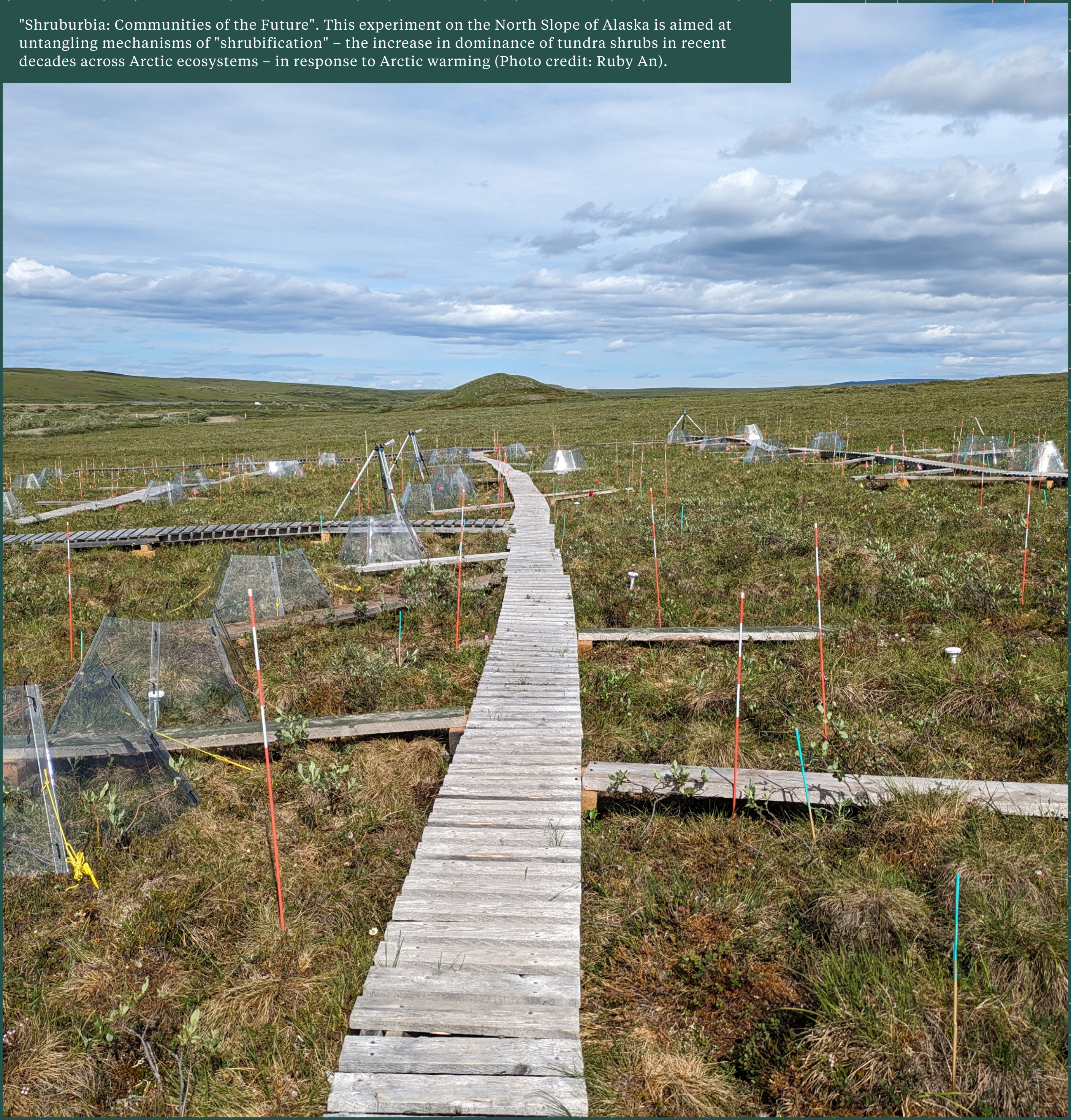
PRINCETON UNIVERSITY

Annual Report 2023

High Meadows Environmental Institute

Carbon Mitigation Initiative

"Shruburbia: Communities of the Future". This experiment on the North Slope of Alaska is aimed at untangling mechanisms of "shrubification" – the increase in dominance of tundra shrubs in recent decades across Arctic ecosystems – in response to Arctic warming (Photo credit: Ruby An).



Cover
A plot-level view inside one of the "open top chambers" in Shruburbia after a snowfall in September 2023. Inside the chamber, temperatures are increased by 2-3 °C, simulating future climate warming and delaying fall snow accumulation (Photo credit: Ruby An).

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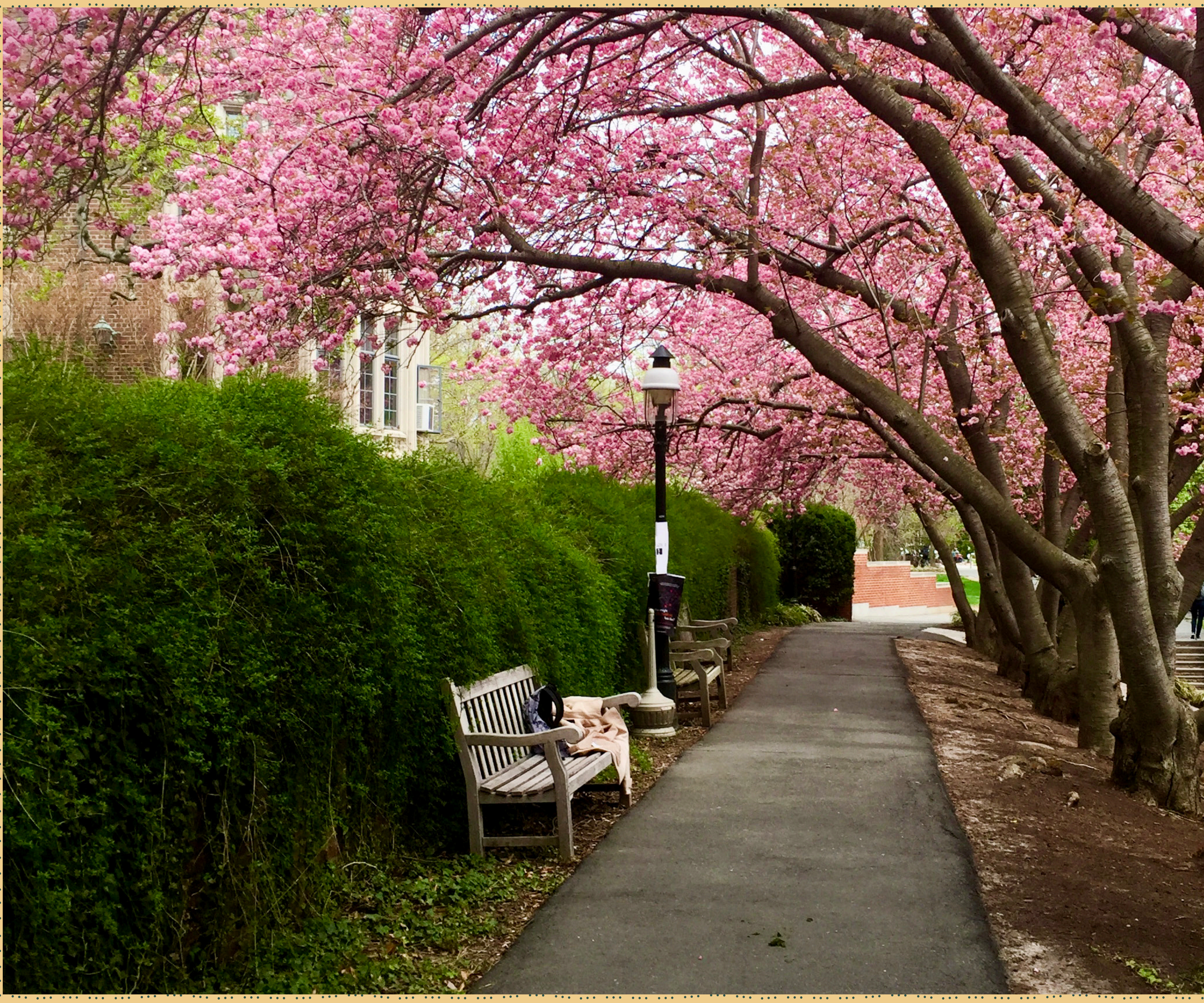

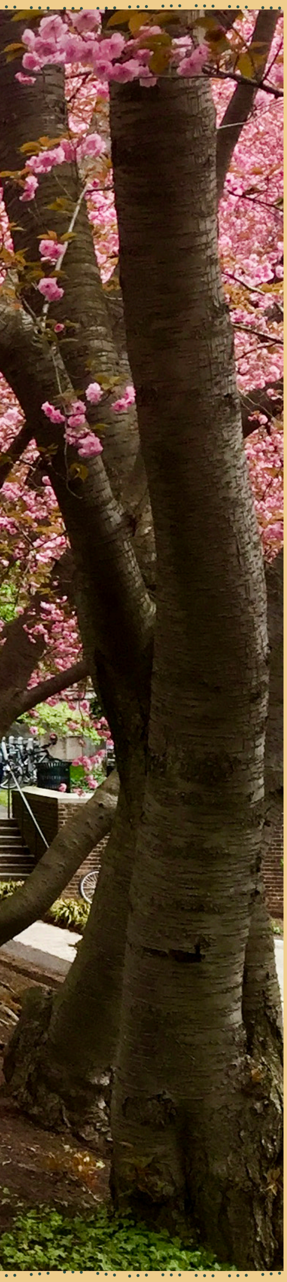

The Carbon Mitigation Initiative (CMI), administered by the High Meadows Environmental Institute (HMEI) at Princeton University, is a 24-year-old partnership with bp. CMI currently funds 21 principal investigators (PIs) and over 60 researchers and students. Teams of scientists, engineers, and policy 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.

Minimizing Reactive Nitrogen Emissions From Ammonia Energy

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At a Glance

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.

Research Highlight

Hydrogen (H_2) has the largest potential to be the low-carbon fuel of the future because of its versatility and scalability. Large-scale international H_2 production projects are underway, with many anticipating the growth of a robust international H_2 trade between renewable-rich regions and demand hubs. However, H_2 direct transport faces challenges due to its low energy density, requiring either extremely low-temperature liquefaction (<-253 C) or high-pressure compression (300-700 bar). Both operations are technologically and economically demanding. They are also prone to risky leakage, with obvious drawbacks linked to economic losses, safety risks, and even climate impacts due to H_2's indirect greenhouse gas (GHG) effect.

Converting hydrogen into ammonia (NH_3) through the Haber-Bosch process ($N_2 + 3\,H_2 \longrightarrow 2\,NH_3$) is arguably the most promising strategy for H_2 long-distance transport. This industrial process is already applied at scale (180 Mt NH_3/y), mostly to produce agricultural fertilizers. Ammonia would offer advantages like storage at more reasonable conditions, mature transport infrastructure, and the ability to be converted back into hydrogen or burned as a fuel. Overall, this strategy holds promise for developing an ammonia-based economy, with ongoing projects exploring NH_3 use in vessels and power plants. Yet, researchers and industry need to address the concerns about ammonia emissions and environmental impacts.

Ammonia (NH_3) is a corrosive and toxic gas that can cause air and water pollution and harm ecosystems and human health. Despite mature infrastructure and regulations, satellite observations reveal that industrial NH_3 production plants are hotspots of ammonia emissions (Figure 1.1). In the ammonia economy, emissions from pipelines, distribution and storage systems, fuel stations, and combustion and cracking sources may also occur. Additionally, undesired emissions of nitrogen oxides (NO_x) and nitrous oxide (N_2O) could occur during unabated or improper ammonia combustion. Together, these emissions would add another significant perturbation to the nitrogen cycle, a crucial aspect of Earth's ecosystems that agricultural activities have already disrupted.

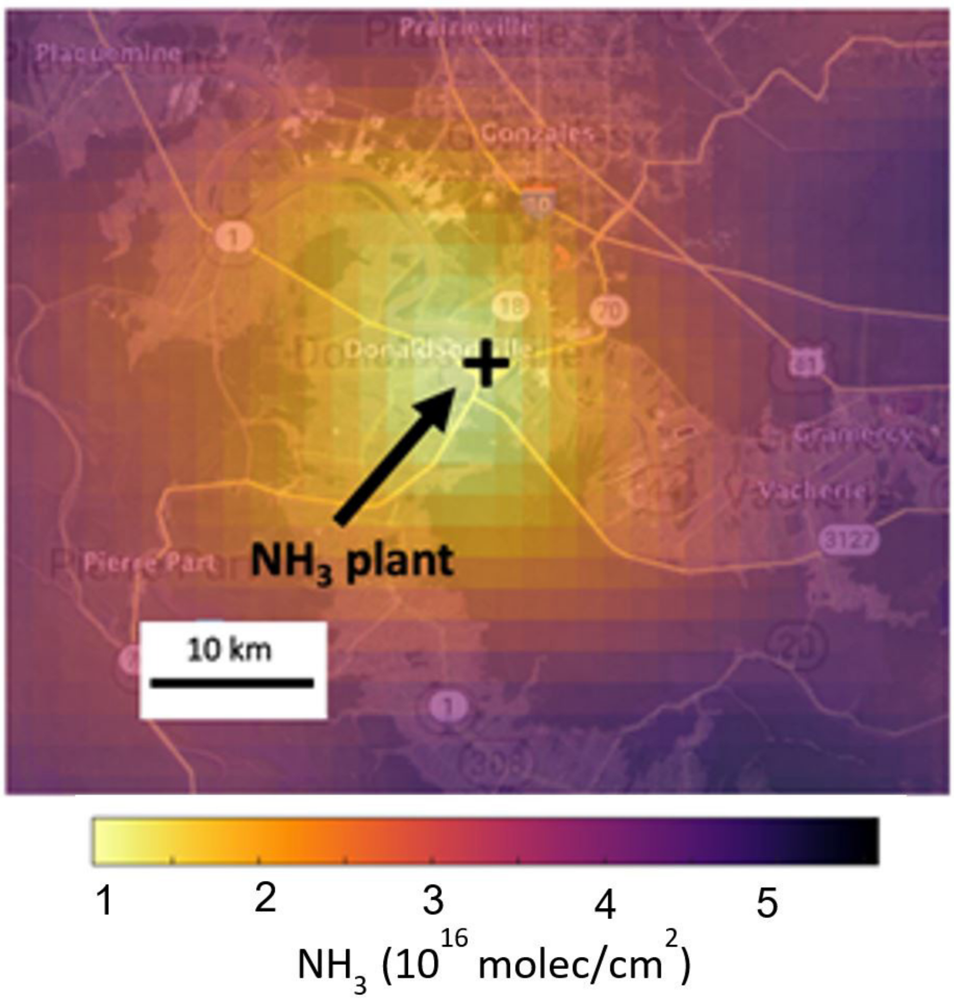
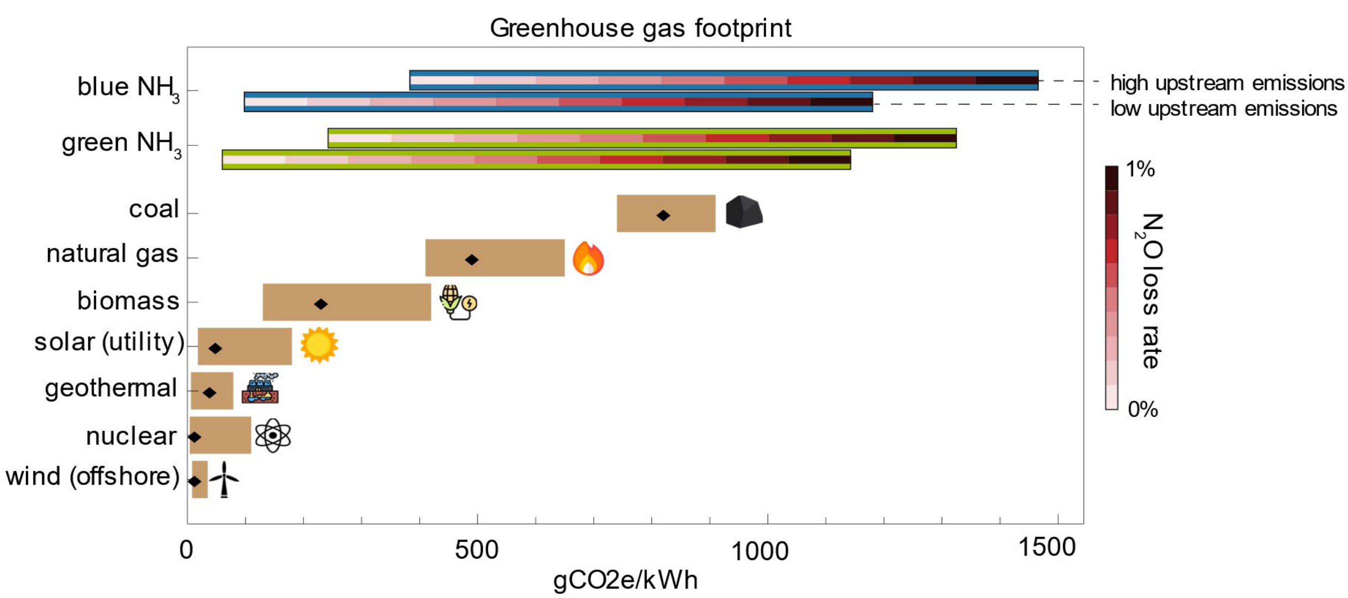


Figure 1.1. Satellites reveal ammonia leaks from the largest (≈4 Mt/y) production facility in the United States (Donaldsonville, Louisiana).

The potential emissions of nitrogen compounds will depend on the amount of ammonia produced and the losses due to leakages and undesired byproducts during combustion. For example, if ammonia fuel achieves a market penetration of around 5% of the current global primary energy demand (≈30 EJ/yr), ammonia production would need to increase to 1,600 Mt NH_3/y, around ten times the current level. If only a small percentage (0.5 to 5%) of the nitrogen in ammonia is lost due to leakages or undesired emissions during combustion, the resulting perturbation of the global nitrogen cycle could be between 6 and 65 Mt N/y. The upper limit is around 50% of the global impact of fertilizers (≈120 Mt N/y).

The efficacy of ammonia as a mitigation solution depends on the potential emissions of nitrous oxide (N_2O). N_2O is a greenhouse gas (GHG) around 300 times more potent than CO_2 and is the leading anthropogenic contributor to stratospheric ozone depletion. Emissions could occur due to unwanted reactions during ammonia combustion. With a 1% nitrogen conversion of ammonia into N_2O, ammonia combustion would have a GHG footprint worse than coal (Figure 1.2). Therefore, it would cause more climate damage than conventional fossil fuels. Though high-temperature combustion generally leads to much lower final N_2O levels, challenges like local quenching during off-design conditions may affect emissions, requiring tradeoffs with other system performance metrics.

Figure 1.2.
GHG footprint of ammonia compared to other sources for electricity generation. Upstream emissions of ammonia production are taken from the IRENA report (2022), with blue ammonia derived from a range of fossil fuels with carbon capture and storage. Values for the other energy sources are from the IPCC Report, with black diamonds standing for median values (Schlomer et al., 2014).



To maximize the benefit of ammonia adoption in the energy sector, it will be necessary to address the environmental challenges through proactive engineering measures before implementation. Identifying worst-case scenarios for ammonia systems can highlight areas of concern during development and optimization. Alternative combustion strategies, ammonia cracking, and existing technologies for converting emissions back into nitrogen offer potential solutions. Early evaluation and learning from past mistakes are crucial for a smooth transition to a more ammonia-based energy system.

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INVESTIGATORS: XINNING ZHANG AND LINTA REJI

At a Glance

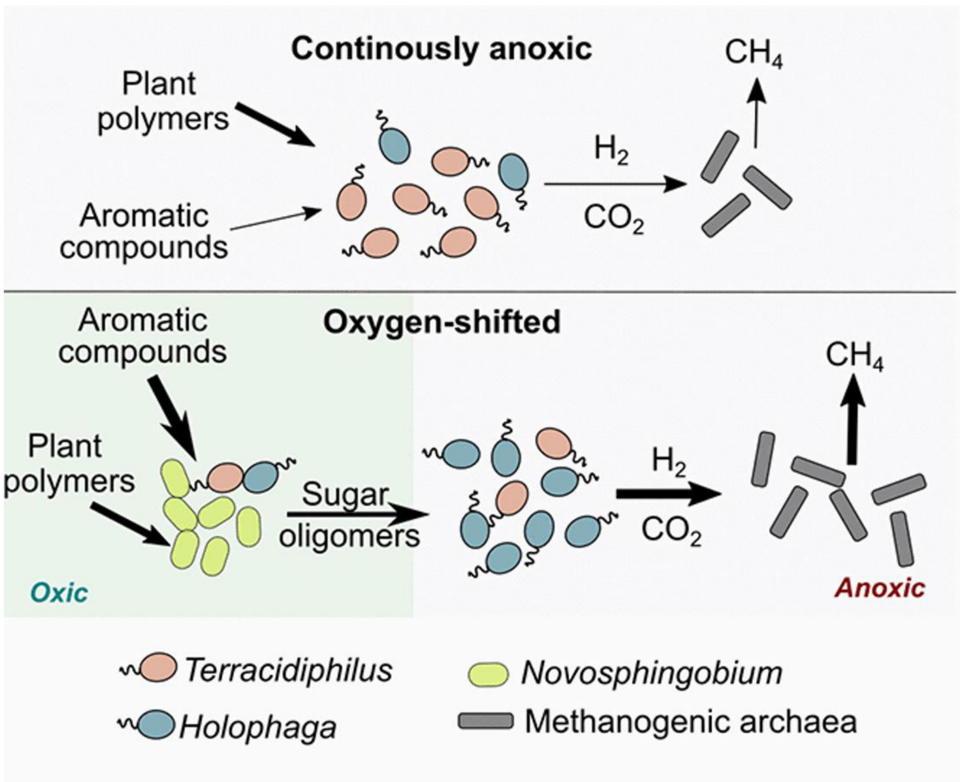
Methane (CH_4) is the second most important anthropogenic climate forcer after carbon dioxide. Determining the importance and mechanisms of different anthropogenic and natural methane sources and sinks across temporal and spatial scales remains a fundamental challenge for the scientific community. Wetlands 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.

Research Highlight

Atmospheric CH_4 has risen to levels roughly 150% above preindustrial concentrations due to human activities. These levels continue to rise despite a short period of stabilization between 1999 and 2006. Wetlands are geographically and biogeochemically diverse environments that together constitute the largest and most variable sources of methane to the atmosphere. CMI Wetland Project researchers are investigating the microbial, chemical, and hydrological pathways that regulate methane emissions from diverse wetland systems that vary in biogeochemical composition and hydrologic environment.

Current research (Reji et al., in preparation) builds on prior CMI discoveries that transient oxygenation associated with hydrological variability unlocks a microbial "latch" on wetland carbon flow that ultimately makes mineral-poor, peaty wetlands drastically more methanogenic (Wilmoth et al., 2021). The researchers have pieced together fragments of genetic information from *Sphagnum*, a genus of peat moss. The researchers are using these microbiomes to recreate microbial genomes. This has allowed the researchers to show that transient oxygenation selects for different keystone microorganisms at multiple steps of the microbial food chain underlying peat carbon conversion into methane (Figure 2.1, Reji et al., 2022).

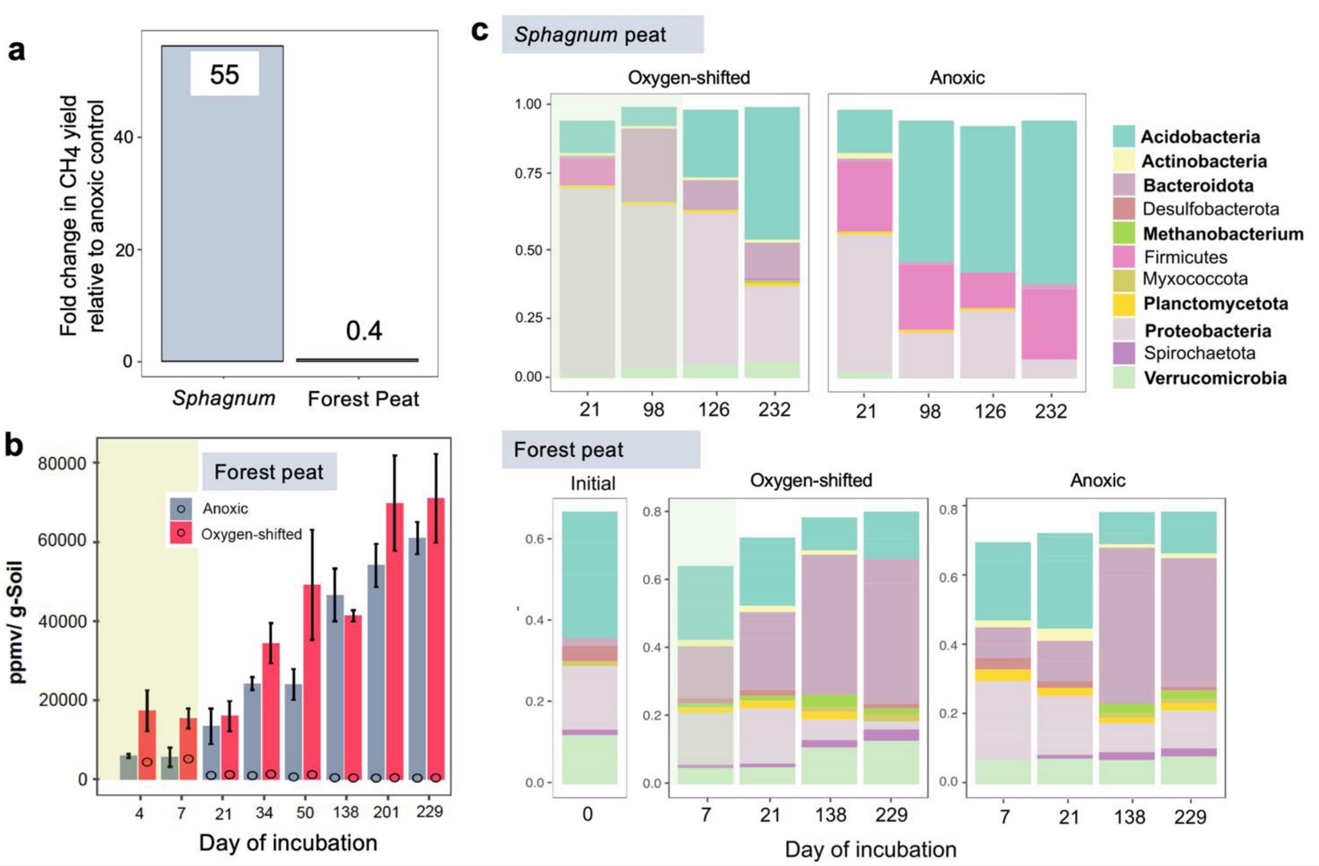
Figure 2.1.
Transient oxygen exposure triggers a shift in microbial community succession during microbial degradation of complex aromatic peat carbon that promotes methane formation (Reji et al., 2022).



Reji et al. (in preparation) examine wetlands along a freshwater to saltwater continuum. The goal is to better constrain the effects of hydrologically driven oxygen variability on methane emissions from a greater diversity of wetlands. This includes an organic-rich *Sphagnum*-dominated peat in a coniferous forest, a mineral-soil marsh, and a saltmarsh. The results indicate that different wetland types respond differently to changes in oxygen levels. Unlike in *Sphagnum* peat from a peat bog (Wilmoth et al., 2021), methane emissions in the forest peat were largely unaffected by oxygen exposure (Figure 2.2a). A similar trend was observed for the mineral soil, or freshwater, marsh. Saltmarsh sediments, in contrast, did not release any methane even under prolonged, continuous anoxia, which refers to an absence of oxygen. Carbon dioxide emissions were generally higher (up to ~threefold) in oxygen-shifted samples across all three wetland types. This was particularly pronounced during the oxic, or oxygen-present, period in both forest peat (Figure 2.2b) and freshwater marsh. The flow of carbon following oxygen shifts was mostly directed towards carbon dioxide. This observation suggested a fundamentally different mechanism regulating the flow towards methane in these wetlands compared to that in a typical *Sphagnum* peat bog.

Geochemical data indicated that the forest peat and the freshwater marsh were much more resilient to short-term (one-week) oxygen exposure compared to the bog-origin *Sphagnum* peat. The microbial data similarly indicated no significant changes in community composition across the oxygen shift (Figure 2.2c). In contrast, community composition in oxygen-shifted forest peat was significantly different compared to anoxic controls (Figure 2.2c). In particular, key microbial taxa linked to altered methane dynamics in the bog-origin *Sphagnum* peat were largely absent in the forest peat. These observations suggest that microbial community composition can be a powerful indicator of wetland responses to pulse disturbances – in this case, changes in oxygen that are driven in nature by shifts in hydrology.

Figure 2.2a-c.
(a) Fold change in total methane yield between oxygen-shifted versus continuously anoxic peat. Both peat types were exposed to oxygen for one week, followed by three weeks of anoxic incubation.
(b) Carbon dioxide emissions in Tree Moss peat over incubation time. Green shaded area indicates the period of oxygen exposure.
(c) Relative abundances of major microbial taxa in *Sphagnum* and Tree Moss peat incubations. Green shading indicates the oxic period. Taxa present in both peat types are in bold letters.



Threshold disturbance level required to shift the resilience behavior (i.e., would a longer period of oxygen exposure change the carbon flow in these wetlands) were examined experimentally, exposing forest peat slurries to a much longer oxic period (i.e., four weeks) before they were made anoxic. The longer oxygen exposure did not change methane and carbon dioxide emission trajectories observed in the original experiments. This suggests that methane dynamics in the forest peat may be resilient to prolonged aerobic conditions, such as those occurring during a drought or water-table drawdown. Further ongoing investigations will compare microbial functional profiles across wetland types (using metagenomes and metatranscriptomes). The aim is to better constrain the microbial mechanisms resulting in differential response of wetlands to transient oxygen shift.

The divergent responses of the two *Sphagnum* peat types to oxygen exposure likely results from the interplay between complex environmental factors. This includes vegetation inputs and hydrology that varied significantly between the two peatlands. These results underscore the need to assess the resiliency of peatlands in the context of their divergent ecological settings. Such careful characterization of the environmental heterogeneity is essential for accurately scaling up laboratory observations to predictive global models of peatland methane emission trajectories.

The CMI wetland project has identified the influence of environmental conditions (e.g., oxygen, soil saturation, water table, salinity) and soil molecular form on microbial biodiversity as keys to better constrain and mitigate wetland methane emissions. The researchers urge the adoption of strategies to limit greenhouse gas emissions from natural and constructed wetlands as part of land-based climate solution initiatives in freshwater wetlands (e.g., Wilmoth et al., 2021; Calabrese et al., 2021). Ongoing collaborations with the Bourg, Stone, and Porporato groups at Princeton University (Yang et al., 2021) address how soil minerology and biophysics can be manipulated to support soils-based carbon mitigation efforts.

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Mapping Opportunities for Land-Based Climate Mitigation

PRINCIPAL INVESTIGATOR: JONATHAN LEVINE

At a Glance

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.

Research Highlight

Land-based climate mitigation strategies are actions aimed at increasing carbon storage or reducing greenhouse gas emissions through exploiting the natural processes occurring in vegetation and soils. These actions are a critical component of nearly all climate mitigation plans. How and where land-based mitigation will be put into practice across the globe, however, remain unknown. Both nature-based (e.g., reforestation) and technology-based (bioenergy with carbon capture) solutions are needed to reduce future climate change. Both require land but, unfortunately, they are rarely studied together. As a consequence, whether and how different methods of increasing carbon storage compete for land remains poorly explored.

To help fill this gap, the Levine group synthesized information on the land requirements and carbon benefits of 19 different land-based climate mitigation strategies. These strategies can help stabilize the climate by (1) avoiding the loss of carbon-dense ecosystems; (2) restoring carbon-dense ecosystems; (3) modifying agricultural and forestry management practices to reduce emissions and increase sequestration; or (4) converting habitat to store additional carbon in aboveground biomass (e.g., afforestation). For each strategy, the group used satellite imagery and spatial data products to estimate the distribution of land biophysically suitable to climate mitigation via each mitigation strategy at a high spatial resolution (Figure 3.1).

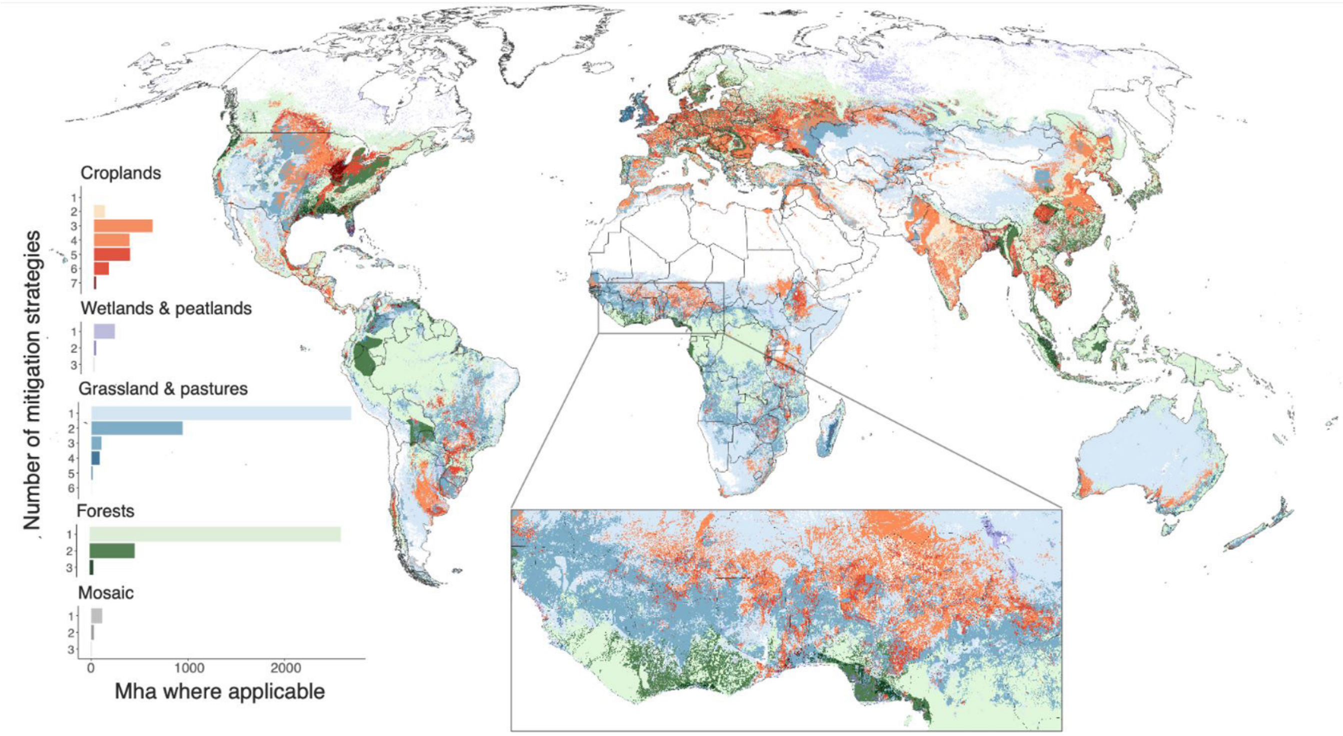


Figure 3.1.
Global distribution of the number of land-based mitigation strategies that are possible in different land cover types across Earth. Legend bars represent the total area (in millions of hectares) where that number of mitigation strategies are possible, highlighting the large area of overlapping strategies in croplands and pastures, and the non-overlapping area in forests, grasslands, wetlands, and peatlands. The color scheme denotes the current land cover type, where darker colors indicate a higher number of mitigation strategies are suitable to that region Inset: High resolution (1km) estimate of the number of possible land-based mitigation opportunities in West Africa.

The researchers found that almost a quarter of Earth's land area is suitable for more than one mitigation strategy (Figure 3.1). Within this area, the research group found that many agricultural landscapes are suitable for multiple mutually compatible strategies. This means that multiple actions to store carbon or prevent emissions can be applied to the same landscape. However, the researchers also identified trade-offs between restoration, carbon-smart agricultural management, and expanding bioenergy, indicating conflicts that could arise across much of Earth's land area where mitigation is possible.

The Levine group's analysis gives local stakeholders, communities, and governments a range of options for how plant and soil processes can be used to reduce carbon emissions and increase carbon storage on land. The analysis identifies a large global area where climate mitigation is possible. However, scaling up several of these mitigation strategies over much of their suitable area often precludes the implementation of other strategies in those areas. Consequently, society has important trade-offs to consider when deciding which land-based mitigation strategies to implement. Ultimately, the goal of this work is to help interested parties decide where land-based mitigation should be placed across the globe to maximize carbon storage, biodiversity conservation, and human livelihoods.

Understanding How Economic Incentives Influence Land-Use Decisions

PRINCIPAL INVESTIGATORS: KATHY BAYLIS, ROBERT HEILMAYR AND ANDREW PLANTINGA

At a Glance

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.

Research Highlight

Land-based climate solutions (LBCS) have the potential to mitigate climate change, protect biodiversity, and affect food security. However, there is little evidence detailing how responsive private landowners will be to incentives that seek to encourage changes in land use. The emLab project seeks to fill this gap by quantifying how responsive land-use decisions are to financial opportunities, and how the impacts of these incentives vary by policy design and across regions, political regimes, cultures, and economic systems. Understanding if and how much land-use decisions respond to financial incentives will help policymakers and practitioners find the most effective solutions that improve efficiency and equity.

There are three main workstreams of this project. The first investigates how the rate of deforestation responds to crop price fluctuations on both global and regional scales. By quantifying landowners' responsiveness to financial incentives, the research team can simulate how land use decisions might change under different carbon prices. These carbon prices can be implemented as a tax on the carbon released through deforestation or as a subsidy for avoided carbon emissions through avoided deforestation, such as payment for ecosystem services. Using these simulations, the emLab team can compare the carbon savings, welfare impacts, cost-effectiveness, and distributional consequences of taxes and subsidies that seek to achieve emissions reductions from avoided deforestation.

Initial findings from this workstream underscore the large potential for relatively low-cost emissions abatement from avoided deforestation (see Figure 4.1a, dashed line). However, this potential depends upon policymakers' ability to target payments towards forests that are at threat of being cleared. If policymakers have incomplete information about local incentives for deforestation, they may set incorrect baselines from which they would pay land users. If those baselines are too conservative, land users may opt out of the program, reducing the abatement that can be achieved by the program (yellow area in 4.1a). In contrast, if the baseline is too generous, the policy will pay land users who would not have deforested in the absence of the policy (purple area in Figure 4.1b). Such payments for non-additional changes in deforestation could undermine confidence in carbon markets.

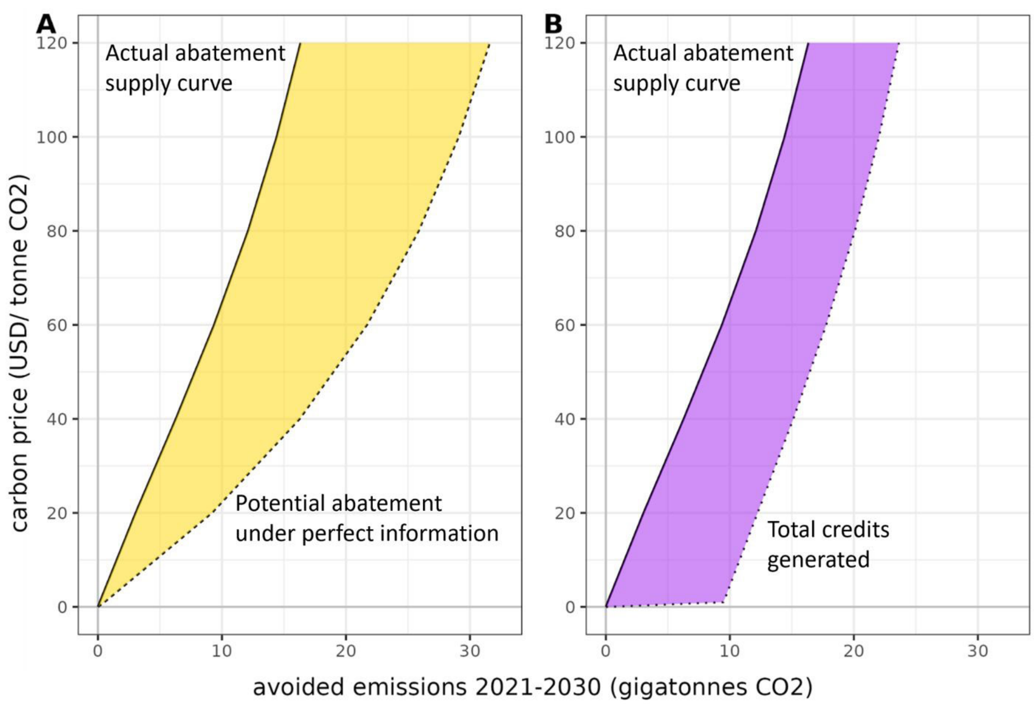


Figure 4.1a-b. Aggregate avoided emissions from deforestation reductions as a function of a carbon price per tonne CO_2. (a) Dashed line: avoided emissions under full information; solid line: avoided emissions under asymmetric information; yellow area: opt-out of program due to underestimation of counterfactual deforestation. (b) Dotted line: total payments to participants in the program; purple area: payments for non-additional emission savings.

While the first workstream shows the mitigation potential from policies to incentivize environmental conservation, such policies are situated in a broader economic, environmental, and institutional context. The second and third workstreams of the project examine the importance of context by exploring focused case studies of LBCS policies in India and Brazil. One important policy-relevant lesson that emerges from these case studies is the risk of increases in unregulated emissions when LBCS policies are narrowly targeted. For example, emLab's research in Brazil highlights that incentives for climate-smart agriculture may discourage forest regeneration if agricultural incentives are not coupled with complementary policies that reward carbon sequestration in forests. Similarly, research in India explores whether existing methane offset protocols that reward changes in rice field water management might simultaneously encourage elevated emissions of nitrous oxide. Together, these two case studies underscore how LBCS policies can be designed to achieve emissions reductions that are not undermined by unintended increases in unregulated emissions.

Quantifying the Carbon Footprints of the World's Largest Mammals

PRINCIPAL INVESTIGATOR: ROBERT PRINGLE

At a Glance

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.

Robert Pringle's research group is using remote sensing and field experiments to understand carbon budgets in African savannas. Here, pilot Tom Lautenbach prepares to launch an unoccupied aerial vehicle bearing a high-resolution LiDAR sensor to map plant biomass in Mozambique's Gorongosa National Park. (Photo credit: Andrew Davies)

Research Highlight

Large herbivores eat vast quantities of plant biomass and alter ecosystems in many ways. But how do they affect ecosystem carbon budgets? This question has shot to the forefront of ecology over the last five years with a stream of high-profile publications by leading scientists, some of which offer a bullish assessment of the potential that herbivores may increase net carbon storage. However, the available data do not yet paint a clear picture, much less a rosy view. Some models and data indicate that "megaherbivores" such as elephants may boost carbon storage by dispersing seeds of large trees with dense wood, which in turn are harder for elephants to topple. Similarly, dense herds of grazers, such as wildebeest, may enhance tree cover by trimming grass that would otherwise fuel fire. Other studies, however, show that elephants can cause substantial reductions in aboveground tree biomass, especially in conjunction with fire. Meanwhile, scientists are only beginning to investigate the impact of these above-ground processes on soils, which hold the majority of total carbon stored in savannas.

Understanding the extent to which large herbivores positively, negatively, or neutrally influence carbon sequestration and storage is essential for evaluating the viability of carbon offset projects and the proposition that these could be extended to include conservation and restoration of threatened wildlife. Until then, the jury is out, and a 2023 *Atlantic* article quotes Pringle as cautioning that wishful thinking should not be allowed to drive carbon-policy decisions (https://www.theatlantic.com/science/archive/2023/12/elephant-conservation-carbon-storage-climate-change/676204/).

The Pringle group is searching for answers in dry savannas in Kenya and a wetter savanna-forest matrix in Mozambique. One forthcoming study from Kenya used high-resolution LiDAR to map all trees and understory plants in 36 experimental plots that exclude different herbivore species. The study shows that herbivores reduce herbaceous plant biomass by roughly an order of magnitude, and that elephants alone reduce tree cover by roughly fourfold despite having no effect on the total number of trees. Other ongoing work is analyzing the carbon content of soils at different depths in the same herbivore-removal plots.

Wildlife populations in Mozambique's Gorongosa National Park are steadily growing after being driven to the brink of extirpation during a civil war in the 1980s. This dynamic scenario presents opportunities to study how the ”rewilding” of large herbivores influences carbon stocks. Preliminary analyses using remote sensing suggest a dramatic and unexpected trend: carbon stored in aboveground woody vegetation has increased by as much as 6 Mg per ha (megagrams per hectare) from 2010-2020 even as populations of elephant and other wildlife have increased, while the surrounding human-dominated buffer zone shows the opposite trend (Figure 5.1). These trends may be driven by fire, which has decreased inside the park—perhaps owing to reduction of fuel loads by grazing herbivores—while remaining relatively constant in the buffer zone (Figure 5.2). Remotely sensed estimates of soil carbon stocks suggest a parallel pattern, although this result requires further validation. As in Kenya, the team is pursuing a deeper understanding by using experimental herbivore removals together with soils analysis and high-resolution drone-based LiDAR imaging.

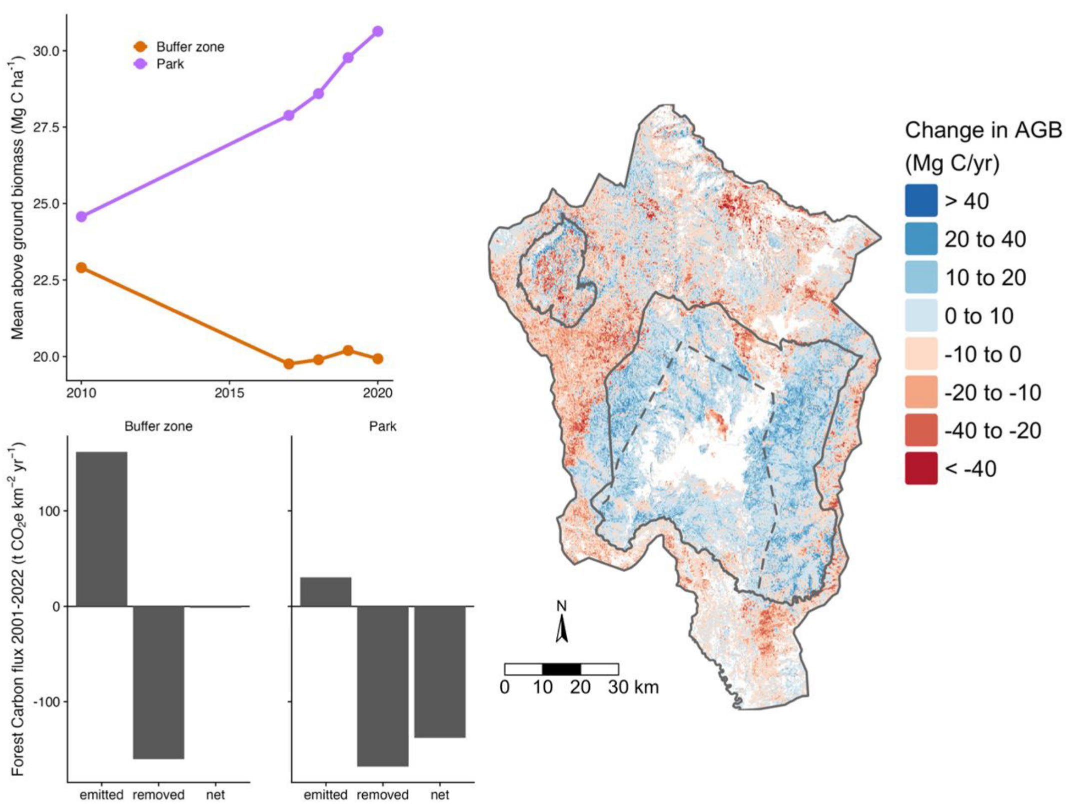
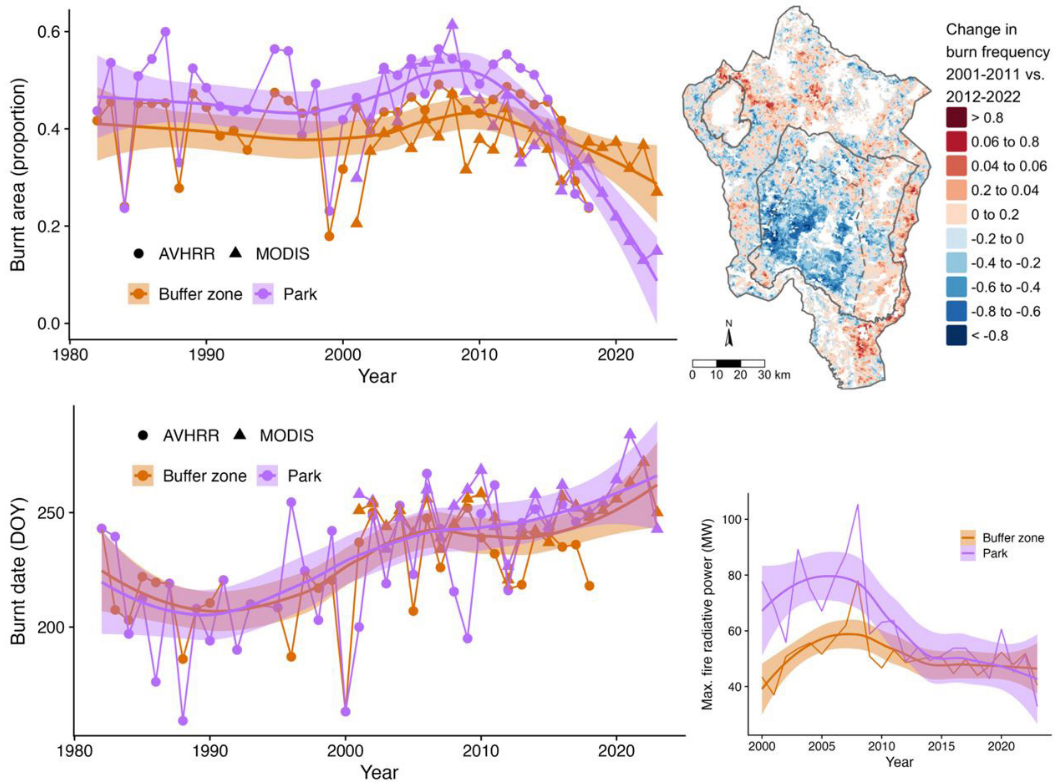


Figure 5.1. Aboveground woody biomass increased in Gorongosa National Park while declining in the human-dominated buffer zone. The largest increases in aboveground woody biomass, predicted using spaceborne radar and LiDAR at 100m resolution, were along drainage lines, particularly in the gorges of the elevated Rift Valley rims in the western and eastern sections of the park.

Figure 5.2.
Burnt area and fire intensity have declined in Gorongosa National Park while remaining relatively constant in the buffer zone. Declines in proportional burnt area in Gorongosa may be due to the recovering densities of grazing herbivores, which reduce fuel for fires. The map illustrates absolute burn frequency change, which ranges from -1 (11/11 years burnt 2001–2011 and 0/11 years burnt 2012–2022) to +1 (0/11 years burnt 2001–2011 and 11/11 years burnt 2012–2022). Seasonal timing of fire (Burnt date) was comparable between Gorongosa and the buffer zone, but fire intensity in the park has declined to a level comparable with the buffer zone, again consistent with reductions in fuel loads by grazing herbivores.



Together, the preliminary results from this work are in keeping with the idea that large herbivores can indeed have profound effects on terrestrial carbon storage. The direction of these effects, however, is not straightforwardly predictable and likely hinges on the interplay between the living and non-living environments.

Assessing Carbon Emission Impacts of Forest-Based Bioenergy

PRINCIPAL INVESTIGATOR: ERIC LARSON

At a Glance

Researchers in Eric Larson's group have developed a framework for assessing the dynamic lifecycle greenhouse gas (GHG) 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.

Research Highlight

When biomass is used for energy, the biogenic carbon released into the atmosphere is often assumed to be carbon net-neutral. This is a reasonable assumption for biowastes and for food-crop residues harvested and used on an annual basis. In contrast, using biomass from managed forests for energy can result in an initial "carbon debt." This term refers to net carbon emissions to the atmosphere relative to a counterfactual scenario where there is no new demand for bioenergy feedstocks. The carbon debt may be "paid back" over time through forest growth and the substitution of fossil energy with bioenergy. Some studies suggest that the use of forest bioenergy can often sequester more carbon than in the counterfactual scenario (Daigneault et al., 2012). However, other studies suggest that forest bioenergy will generate a carbon debt that can never be paid back (Schulze et al., 2012). Such widely varying conclusions are due in part to differences in methodologies and assumptions (Bentsen, 2017; Cowie et al., 2021; Galik and Abt, 2012; Ter-Mikaelian, 2015). Equally important factors include the geographic location, existing market conditions, and the age class profile and dominant species of the forest resource under consideration.

To help illustrate the complexities of forest-bioenergy GHG emissions accounting, Larson and his group developed a framework (Figure 6.1) for assessing the lifecycle GHG impacts of hypothetical bioenergy projects. They applied the framework to case studies involving utilization of feedstocks from different specific forest basins in the U.S. south (Figure 6.2). The extent of each basin represents a plausible area from which a bioenergy facility might source feedstock. There are some 87 million hectares of managed forests across the U.S. south that today provide feedstocks for forest product industries and serve a variety of other purposes. Nearly 90% of this area is privately held. Private timberland owners are known to adjust their forest management practices based on changes in prices they receive for wood and policy incentives (Amacher et al., 2009). This, in turn, determines harvest rates, forest growth conditions, and ultimately forest carbon storage (Mei, 2023).

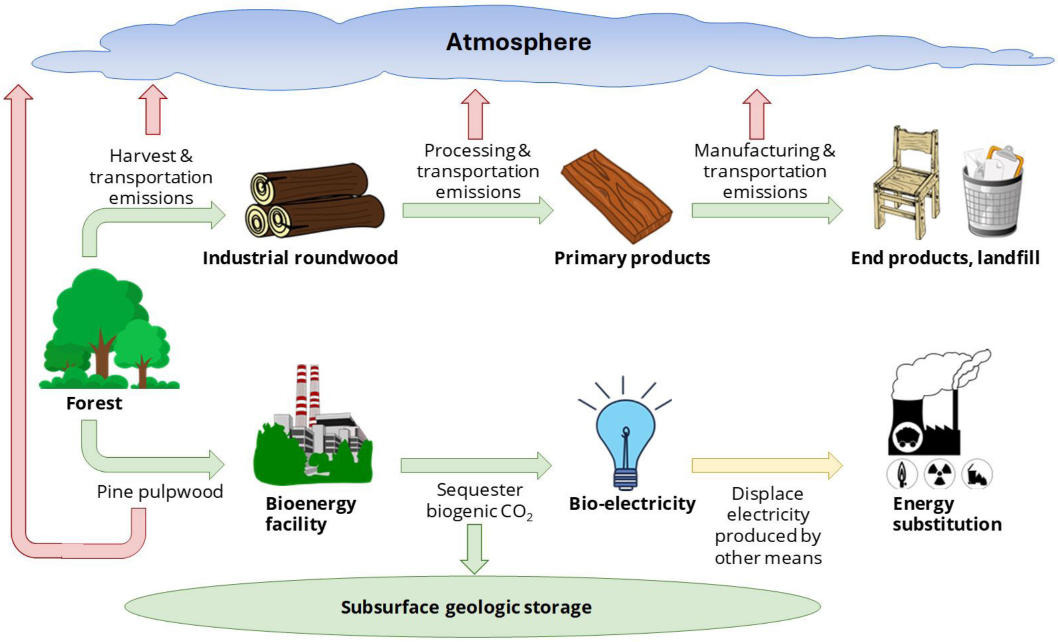


Figure 6.1. Framework for dynamic lifecycle greenhouse gas emissions analysis of forest-biomass use for energy, considering forest carbon storage, non-biogenic carbon emissions in supply chains, bioenergy substituting fossil energy, carbon storage in forest products (and landfills at end of life), and any geological storage of biogenic carbon associated with a bioenergy facility.

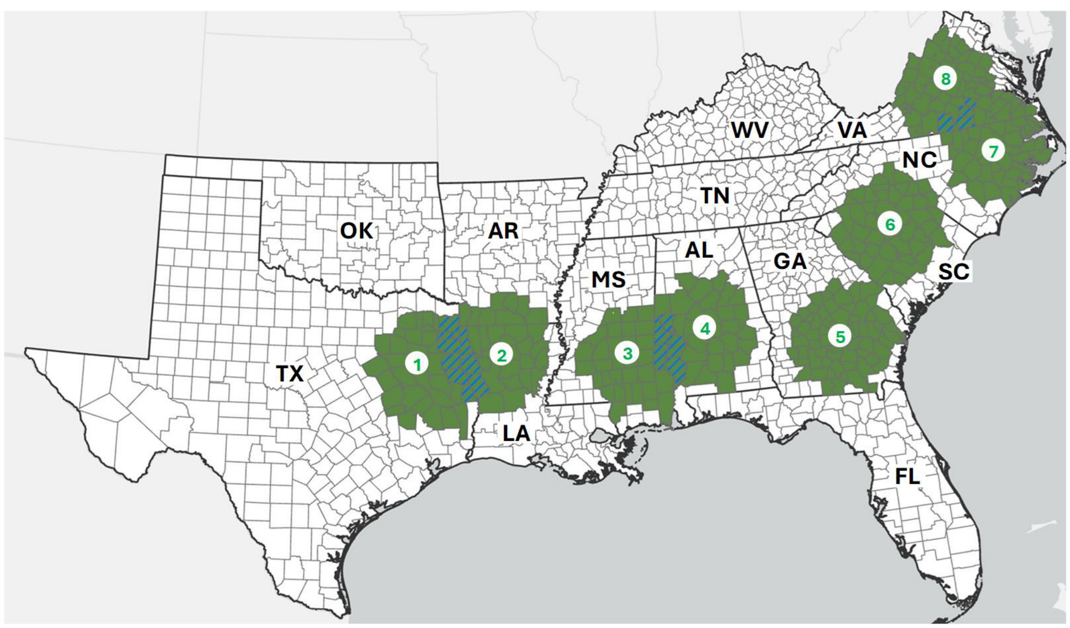


Figure 6.2. Eight case-study forest basins were analyzed. Each includes all counties that lie wholly or partially within a 75-mile radius of a central hypothetical bioenergy facility site.

The researchers captured such owner behavior through use of the Sub-Regional Timber Supply model (Henderson et al., 2023). This model was developed specifically for timber market conditions unique to the U.S. South. These conditions include the region's predominantly commercial use of southern yellow pine, its reliance on harvests from private land, and the capacity at the margin for forest area to expand or contract and/or be converted from natural to managed regeneration depending on changes in timber prices. The model uses data from the U.S. Forest Service Forest Inventory and Analysis (US Forest Service, 2024) and the Timber Products Output database (Coulston et al., 2018). These provide baseline quantities of forest biomass by age and size classes, forest types (e.g., natural pine vs managed pine), and private ownership groups (corporate and non-corporate, which manage forests differently).

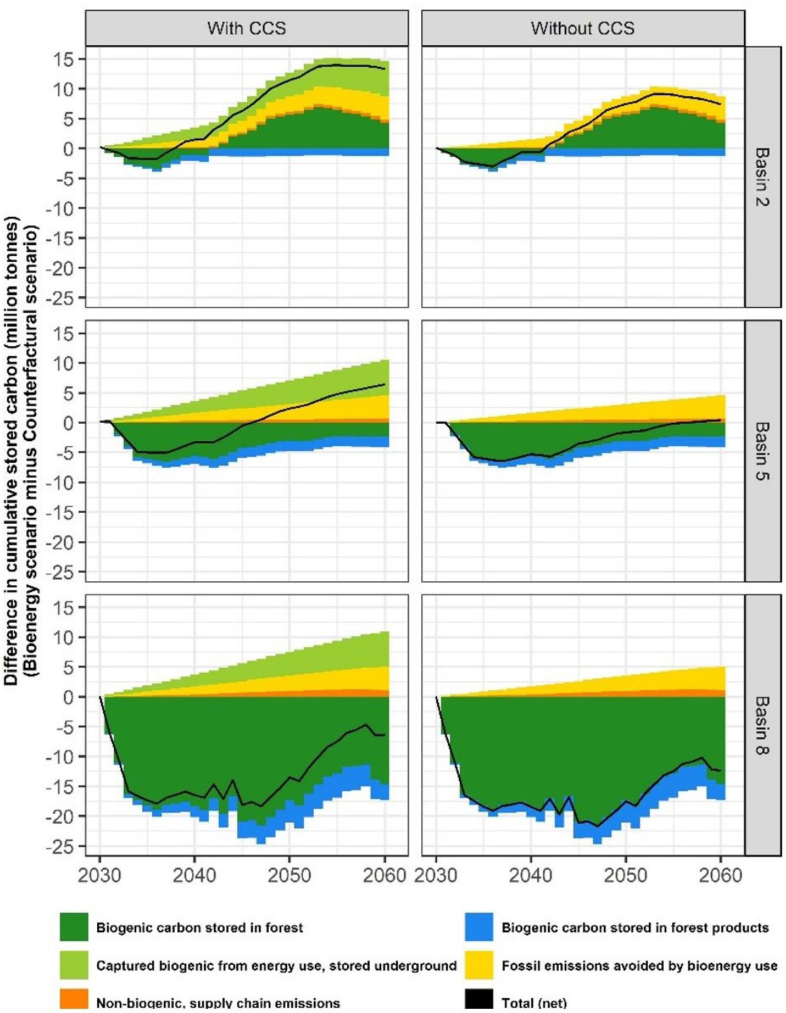


Figure 6.3.
Difference in cumulative stored carbon in a bioenergy scenario versus a counterfactual (no bioenergy) scenario in three case-study basins. In each case, a hypothetical bioenergy facility is assumed to use two million green tonnes per year of pulpwood quality biomass from the basin. Results are shown for bioenergy facilities producing sustainable aviation fuel either with or without CO_2 capture and storage (CCS). See Figure 6.2 for basin locations.

Figure 6.3 shows differences, relative to counterfactual (i.e., non-bioenergy) scenarios, in cumulative carbon stored away from the atmosphere over a 30-year operating life of a bioenergy project. The figure illustrates this for a hypothetical bioenergy facility with and without CO_2 capture and storage (CCS) in three of the modeled forest basins. In each basin, the carbon stored in the forest and in forest products, emitted from supply chain activities and avoided by fossil substitution, are identical for the case with and without CCS. Additional carbon is stored when CCS is employed. In Basin 2, CCS reduces the carbon-debt repayment period from 11 years without CCS to eight years, and the net cumulative carbon stored over the project lifetime is nearly double with CCS versus without. Basins 1, 3, 4, and 7 demonstrate similar carbon behavior as in Basin 2. In Basin 5, the carbon debt without CCS is repaid in 26 years. With CCS, it is repaid in 16 years. In Basin 6, without CCS, the carbon debt was found to not be repaid after 30 years, and with CCS it is repaid in about 25 years. Finally, in Basin 8, forest carbon loss is substantial because of the particular forest conditions found there, and the carbon debt is never repaid even with CCS.

The work of Larson and his group shows that forest-based bioenergy projects in the southern U.S. can display relatively short carbon debt repayment times when drawing feedstocks from certain forest basins, but not when drawing from others. Case-by-case assessments are therefore necessary. In some cases, new wood demands for bioenergy drive expansion of planted forests, which can shorten the carbon debt repayment period. In general, carbon debt repayment will be faster for bioenergy projects that employ CCS than those that do not.

Finally, because forests and associated forest-product markets change over time, assessments of the climate impact of a bioenergy facility are specific to the year in which a facility is envisioned to start operation. For a given forest basin, the climate impact of a project that begins operating in 2040 might be different from the same project starting operation in 2030. These are important considerations for policymakers and bioenergy project developers alike.

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

PRINCIPAL INVESTIGATOR: JESSE JENKINS

At a Glance

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.

Research Highlight

The Zero-carbon Energy Systems Research and Optimization Laboratory, or ZERO Lab, is developing a new, open-source, high-performance macro-energy systems planning model known as MACRO to explore and understand pathways to net-zero emissions. The model optimizes changes in energy supply and network infrastructure across the economy, ranging from electricity, liquid fuels and natural gas to hydrogen, bioenergy, and industrial processes as well as carbon dioxide (CO_2) transport, storage and use.

The electricity sector will play an increasingly expanded and central role in any net-zero emissions energy system (Figure 7.1). It is therefore critical that any model charting pathways to decarbonize the economy accurately captures the dynamics of the electricity sector, the electrification of end uses like transportation and heating, and electricity's use to produce intermediate fuels like hydrogen or synthetic liquid fuels. MACRO is thus an "electricity-centric" model, featuring an unprecedented level of temporal granularity in an economy-wide, macro-energy systems model. This high resolution is critical for accurately planning and ensuring reliable electricity supplies in power systems with high shares of variable, weather-dependent renewable energy sources like wind and solar power.

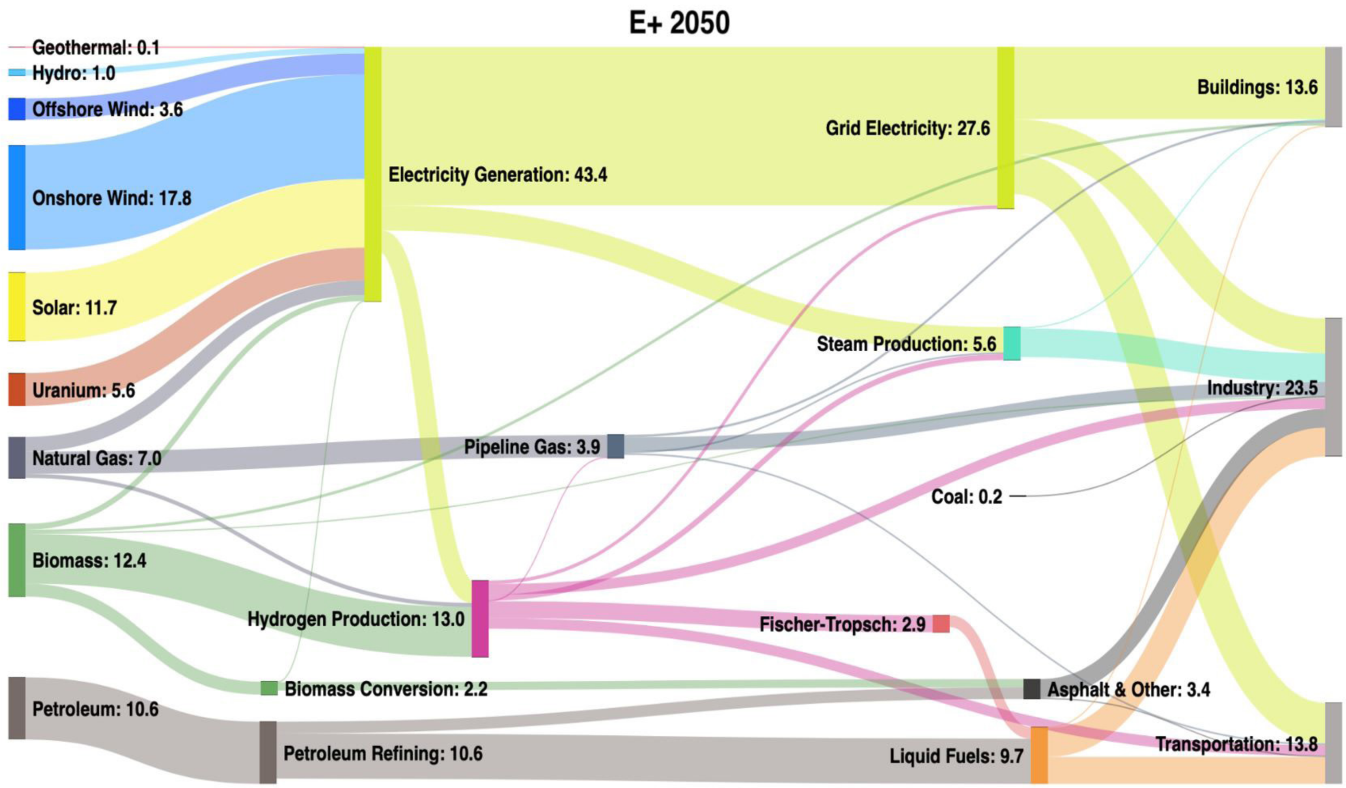

Figure 7.1.
A Sankey diagram shows flows of energy across a net-zero emissions U.S. economy in 2050, highlighting the central role of the electricity sector and high degree of coupling across and between sectors (Larson et al., 2021).

Traditional macro-energy systems optimization models are formulated as a single monolithic optimization problem, or linear programming problem. Unfortunately, the computational requirements of such models, including computing time and memory requirements, scale non-linearly with the size and complexity of the model. This has severely limited previous published analyses, forcing them to represent the electricity sector in a highly simplified manner, by ignoring key technical constraints or operational dynamics. Computational constraints have also caused previous studies to model only a small subset of hours or days in the year (e.g., 20-40 ”representative days”) to try to represent electricity system operations. These abstractions have been necessary to keep traditional models computationally tractable, but can significantly bias results. Any inaccuracy in the representation of the electricity sector will ripple across all other sectors, given the myriad interactions between electricity and other energy networks and industries in a decarbonizing future.

Overcoming these limitations demands new techniques to dramatically improve the computational performance of macro-energy systems optimization models. ZERO Lab has worked for several years on mathematical “decomposition methods” that exploit our detailed knowledge of the specific structure of these models. The strategy is to decompose large-scale problems into numerous smaller subproblems and enable better exploitation of parallel supercomputing capabilities and the application of custom methods that can substantially reduce computational time (Jacobson et al., 2023). The new methods ensure that the computational time scales linearly (rather than quadratically) with temporal resolution while enabling calculations of optimal discrete infrastructure investment and retirement decisions with effectively no increase in computational time. This latter capability is important to capture economies of unit scale in energy systems infrastructure (e.g., transmission lines, pipelines, industrial facilities), which is typically intractable in any other macro-energy systems planning model.

Development of MACRO leverages ZERO Lab's expertise building GenX, a best-in-class, well-established open-source electricity system planning model.[1] The tool will also incorporate development of novel formulations informed by detailed engineering process simulations and techno-economic analyses. The aim is to represent a richer set of technologies and strategies to decarbonize industrial processes such as iron and steel, cement, chemicals and fuels, and industrial process heat requirements that are currently absent from most models.

When fully implemented, the MACRO tool will provide a new, open-source model for use in ZERO Lab's Technology Evaluation Program. This program focuses on evaluating and optimizing low-carbon energy technologies and guiding investment, research, and technology policy decisions. MACRO will also serve as the new workhorse model for a variety of granular, actionable net-zero transition studies conducted with research partners around the world and patterned after the high-impact Net-Zero America study, including the Net-Zero India study supported by CMI.

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1 *See https://github.com/GenXProject/GenX/*

Overcoming Challenges Facing the Execution of Net-Zero Energy Ambitions

PRINCIPAL INVESTIGATOR: CHRIS GREIG

At a Glance

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.

Research Highlight

Princeton's Net-Zero America Study offered a crucial first step in providing a clearer understanding of the implementation challenges. Aided by a number of innovative post-modeling analyses, the project revealed four critical challenges that potentially constrain the speed of the transition:

1. Availability of development capital to mobilize the pipeline of shovel-ready infrastructure projects;
2. Pace of infrastructure deployment given the sequence of inevitable investment decision bottlenecks across interdependent value chains (e.g., sectors, supply chains, enabling infrastructure);
3. Development of community support that is enduring across multiple decades of disruptive engagement, construction activity, and changes in the natural and built environments; and
4. Workforce mobilization that involves both an enormous mobilization of additional capacity, but also justly repositions workers displaced in the phase-down of incumbent sectors.

For 2023 and continuing into 2024, Chris Greig and his research team have focused on three main areas:

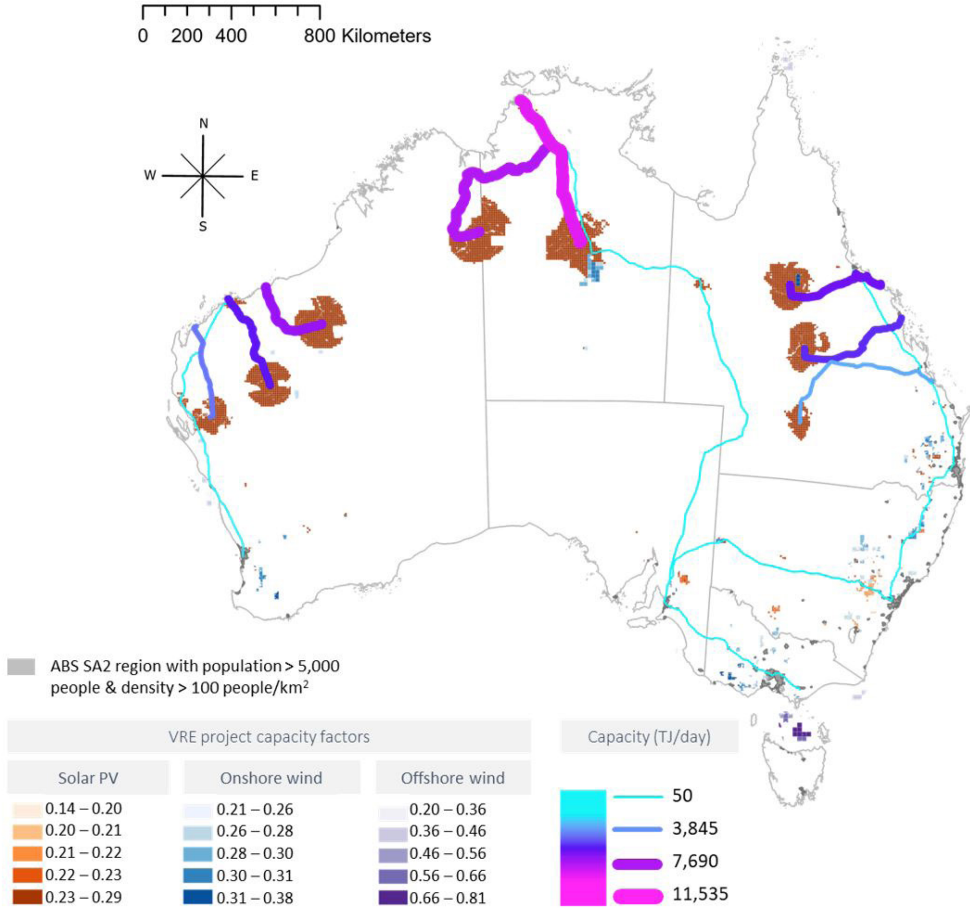
(i) Ongoing implementation of net-zero national studies, e.g., Net Zero Australia (Davis et al., 2023), which was completed in July 2023 and is now focusing on the potentially largest contributors to future cumulative emissions. Net-Zero India has been in scoping phase for nine months. Scoping entails acquisition of fine resolution datasets for energy demand, production, infrastructure, land use, and demographics; framing scenarios; establishing local research teams and governance structure; and fundraising. The current plan is to kick off modeling and down-scaling by June 2024, and to commence scoping studies for Indonesia and Pakistan by the end of 2024, subject to fundraising efforts.

(ii) Interdisciplinary research that seeks to elucidate insights and methods to help identify and anticipate deployment bottlenecks related to the four critical challenges described above (Greig et al., 2023; Emodi et al., 2023; Mayfield et al., 2023); and to develop tools to better represent the onset and the impacts of such bottlenecks in macro-scale models.

(iii) Related to (ii), recent research around a new paradigm in the practice of infrastructure development undertaken in collaboration with a major Engineering, Procurement and Construction (EPC) firm (Anderson et al., 2023). This has revealed the central role of trust among the diverse array of actors engaged in, impacted by, or influential in the energy transition. A current deficit in trust is promoting investment hesitancy, including a deficit in horizontal trust among stakeholders engaged in implementation, and in vertical trust between implementors and affected populations or those who influence public opinion. This restricts the collaboration, sharing of insights, and transparency necessary to catalyze enduring and widespread cooperation and support. We have initiated a new research collaboration to develop a framework for developing the enduring trust needed to facilitate a mid-century net-zero transition.

(iv) Translations of modeled transition pathways into asset portfolio pathways for companies that own and operate energy and industrial infrastructure. This would extend recent work to align corporate assets and production with IAM pathways that are compatible with a global average temperature increase of 1.5°C (Rekker et al., 2023).

Figure 8.1.
Downscaled representation of wind and solar, and major corridors for electricity, hydrogen, and desalinated water transmission/pipeline infrastructure for the Net Zero Australia Study. Note that Net Zero Australia scenarios were framed to transition the domestic economy to net-zero by 2050; and substitute coal and LNG exports clean hydrogen/ammonia which are phased out/in between 2030 and 2060.



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Tropical Cyclones from Weather to Millennial Timescales

PRINCIPAL INVESTIGATOR: GABRIEL VECCHI

At a Glance

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.

Research Highlight

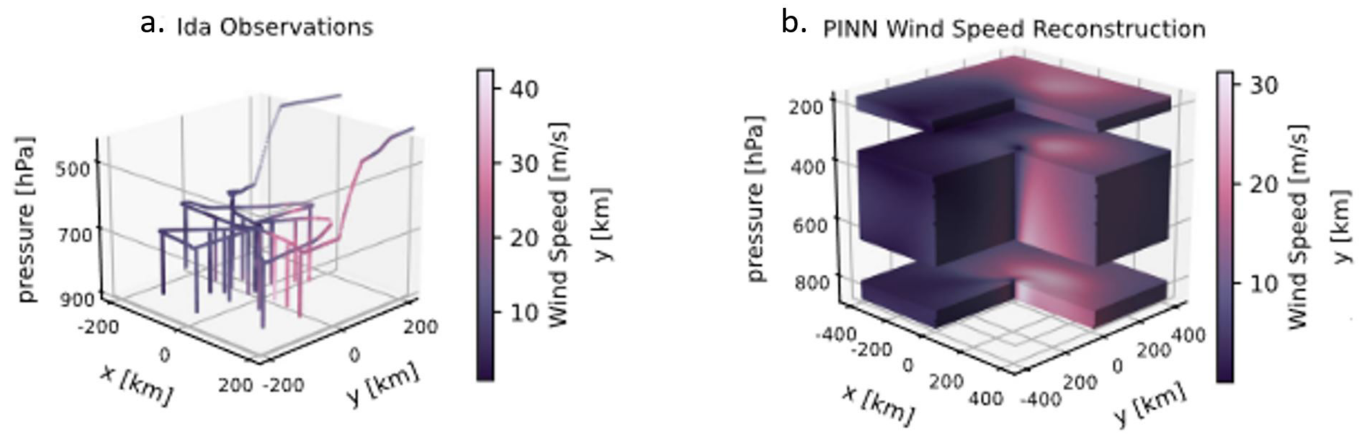
Tropical cyclones (TCs) are of profound societal and economic significance. TC characteristics, such as their track, frequency, wind and rainfall intensity, exhibit variations on a range of timescales. Predicting these variations requires improved understanding of the character of and mechanisms behind these changes. Throughout 2023, Vecchi and his researchers worked to understand the climatic controls on TC frequency (Hsieh et al., 2023) and track (Kortum et al., 2023). They developed a novel machine learning-based method to reconstruct the three-dimensional structure of hurricane winds (Eusebi et al., 2024). This method could help improve weather-scale forecasts of hurricanes and explore the history of and mechanisms behind hurricane variations in the North Atlantic over the past millennium (Yang et al., 2024).

The relatively short historic record of observed hurricanes poses an important limitation to a better understanding of multi-decadal to centennial changes in hurricane activity. While ship-based observations of hurricanes in the Atlantic go back to the 1850s, satellite-based estimates only go as far as the 1960s. Vecchi and his team have been working with colleagues around the U.S. to explore the impact of climate changes over the past millennium on tropical cyclone activity using a reconstruction from sedimentary paleohurricane records and a statistical model of hurricane activity using sea surface temperatures (Yang et al., 2024). The goal is to better understand the variations in hurricane activity. This work indicates that there may have been large centennial changes in Atlantic hurricane activity over the past 1,000 years, resulting largely from natural climate variations. The amplitude of these past changes may be comparable to model-projected changes in Atlantic hurricane activity projected for the coming century. This indicates that future changes arising from increasing greenhouse gases may be temporarily masked (for periods of many decades) or enhanced – providing a complex landscape for adaptation strategies, and complicating interpretation of the historical hurricane record. The researchers found that statistical and dynamical models of hurricane activity, when provided with estimates of ocean temperature changes over the past millennium, are able to recover multi-decadal to centennial scale variations in Atlantic hurricane activity estimated independently from sediment cores. A manuscript detailing this work is in press (Yang et al., 2024).

The Vecchi group continued their work to understand the mechanisms controlling tropical cyclone frequency, building on their novel paradigm of "seeds and probabilities." This research provides a framework for interpreting the impact of large-scale environmental factors on tropical cyclone activity. It shows that one must consider the change in the number of pre-tropical cyclone vortices (or "TC seeds"), and the impact of large-scale environmental conditions on the probability of cyclone genesis from those seeds. Both are needed to accurately account for the sensitivity of tropical cyclone frequency to global forcing, such as the presence of atmospheric aerosols. Previous work, which had focused primarily or solely on the genesis probability, failed to accurately explain the response of TC frequency to forcing. Over the past year the researchers published a study demonstrating that the inter-model spread in TC seeds (and thus TC genesis) in response to warming could be explained by the large-scale radiative energy convergence in the atmosphere, providing a large-scale constraint on global TC frequency change (Hsieh et al., 2023). This work has shown that inter-model spread in TC genesis sensitivity to changing climate is largely driven by differences in the climate-induced-response of pre-TC synoptic disturbances, which can be connected to large-scale changes in vorticity and ascent – and these can be understood in terms of atmospheric energy flux convergence.

Given the risks posed by hurricanes, improved forecasts of the track, intensity and impact of hurricanes are of value. The researchers aim for more precise weather-scale predictions of storms to provide weather forecast models with an accurate representation of the three-dimensional structure of a hurricane at the start of the forecast. Although tropical cyclone winds are energetic and spatially variable, airplane-based observations of storms recover relatively sparse samples. Figure 9.1a shows the wind observations of Hurricane Ida while it was in the Gulf of Mexico on the 27th of August 2021. These observations are confined to the lower atmosphere (below 500hPa) and at discrete locations. The Vecchi group built a hybrid statistical-dynamical (i.e., a "Physics-informed Neural Network", or PINN) method for reconstructing the three-dimensional wind field of tropical cyclones using machine learning/artificial intelligence techniques (Eusebi et al., 2024). As can be seen in Figure 9.1b, the method is able to generate a spatially complete reconstruction of the storm, even outside of the area with observations, and recover the asymmetries in the storm structure. These wind fields will be used in future experimental retrospective hurricane forecasts to explore the potential for improving weather-scale forecasts of hurricane track and intensity.

Figure 9.1a-b.
PINN output trained with a combination of real hurricane hunter observations and SHiELD forecast data.
(a) The locations and magnitudes of Ida flight level and dropsonde wind speed observations recorded roughly between 10z and 12z, Aug. 27.
(b) PINN 3D reconstruction of Hurricane Ida on August 27th, 12z (Eusebi et al., 2024).



Vecchi and his team are using observations, advanced statistical methods, and climate model experiments (Kortum et al., 2023) to explore the mechanisms controlling decadal changes in Atlantic hurricane tracks. They have shown that the recent multi-decadal eastward shift in Atlantic hurricanes (from 1971 to 2020) was not principally a climate-driven signal. The shift included a dominant component associated with random weather fluctuations – highlighting a limited predictability for decadal hurricane track changes. The study further demonstrated that decadal changes in the location of TC genesis have had a larger role than changes in atmospheric steering winds in controlling these multi-decadal changes in hurricane track. This highlights the need to improve our predictions of TC genesis location in order to improve assessments of regional TC risk.

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

INVESTIGATORS: CLAIRE WHITE AND ANITA ZHANG

At a Glance

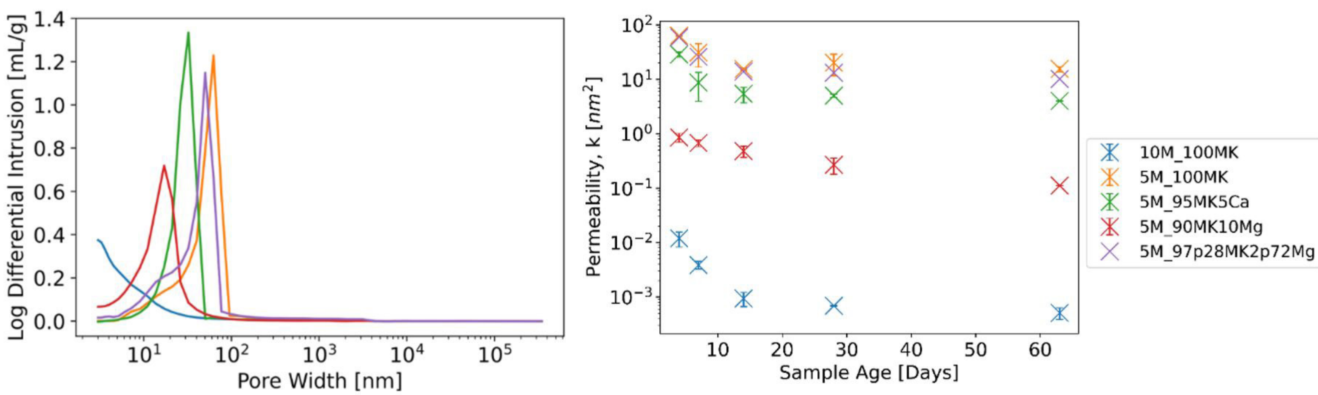
Portland cement is currently the most common type of cement used in concrete manufacture, but it is a significant source of atmospheric carbon dioxide (CO_2) due to the production process. To counter this, White and her group are developing sustainable cements that are alternatives to conventional Portland 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.

Research Highlight

Hard-to-decarbonize industries such as cement face the daunting task of lowering their CO_2 emissions while maintaining product quality and performance. This is particularly challenging for cement and steel, where any change to the chemistry of the material can have long-term, significant ramifications on performance and safety. After water, concrete is the second most consumed resource in the world and is essential to modern infrastructure. However, one key ingredient of concrete, Portland cement powder, currently accounts for approximately 8% of global anthropogenic CO_2 emissions. Alternative cements can offer more sustainable options for producing concrete, thus avoiding a significant portion of CO_2 emissions in the industry. However, our ability to predict the long-term performance of these more sustainable materials is severely hampered by the time it takes to obtain pore structure data of the binder material that controls ingress of harmful chemicals such as CO_2, sulfate (SO_4^{2-}), and chlorine (Cl^-) ions.

Recently, White and her group have been focused on reducing CO_2 emissions associated with alkali-activated metakaolin (AAMK) cements. They are exploring the possibility of lowering the concentration of the activator – the most carbonintensive component of AAMK – without adversely impacting long-term performance. This involves using a small amount of a cation additive such as calcium hydroxide or reactive magnesium oxide to help offset reduced performance at lower activator concentrations. Permeability quantification measures using beam-bending tests and pore neck size distributions obtained by mercury intrusion porosimetry show that both calcium hydroxide and magnesium oxide can improve the durability of AAMK with low activator concentrations (Figure 10.1). On a per-mole-of-cation basis, calcium hydroxide appears to be more effective than magnesium oxide. However, more magnesium oxide can be added without causing a significant premature decline of mixability, making magnesium oxide a promising additive to ultra-sustainable AAMK systems.

Figure 10.1.
(Left) Mercury intrusion porosity results for AAMK systems with two different activator concentrations and with and without cation additives.
(Right) Permeability values as a function of sample age for tested AAMK systems.



White and her group are also studying the characteristics of the ink-bottle pore shape, specifically the inner pore size and the neck pore size. This research uses novel techniques such as neutron grating interferometry and focused ion beam scanning electron microscopy. The hope is that a more comprehensive assessment of cation additives' effects can be carried out in future studies.

White's research is also focused on dissecting how cation additives reduce pore sizes and permeability. The researchers used *in situ* Fourier-transformed infrared spectroscopy (FTIR) and isothermal conduction calorimetry (ICC) to observe alkali activation reactions in real-time (Figure 10.2). Using the FTIR data, the researchers can track changes in the vibration mode associated with the dissolution of metakaolin and the precipitation of gel phases. From ICC, the researchers can measure cumulative heat of each reaction. Preliminary results indicate that both calcium hydroxide and magnesium oxide

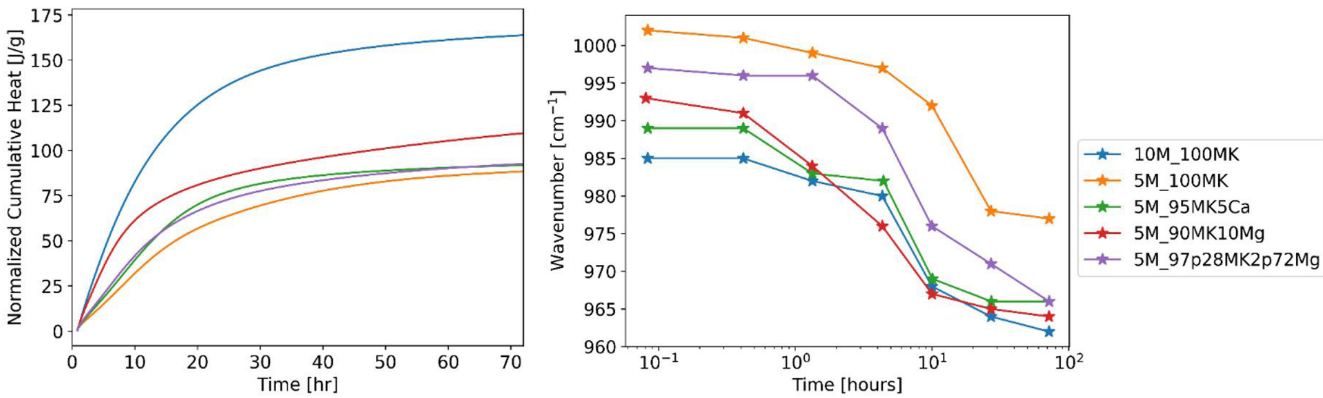


Figure 10.2.
(Left) Cumulative heat flow curves of various AAMK systems, normalized by total sample weights. (Right) Changes in the FTIR vibration mode associated with metakaolin dissolution and gel precipitation.

promote the early dissolution of metakaolin, presumably by increasing the pH of the solvent, thereby resulting in more paste forming. Cation additives also appear to create transient gel phases that may affect the mature paste structure. Additionally, magnesium oxide seems to have some delayed effects on the paste when compared to calcium hydroxide. This difference may explain the two additives' varied influence on the early-age flow property.

White and her group are hopeful about achieving the optimization and customization of sustainable cements. They believe that this can be achieved by understanding the ways in which cation additives enhance AAMK systems and establishing a robust structure-property-mechanism relationship for AAMK.

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Climate Change and Suffocating Oceans

PRINCIPAL INVESTIGATOR: LAURE RESPLANDY

At a Glance

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.

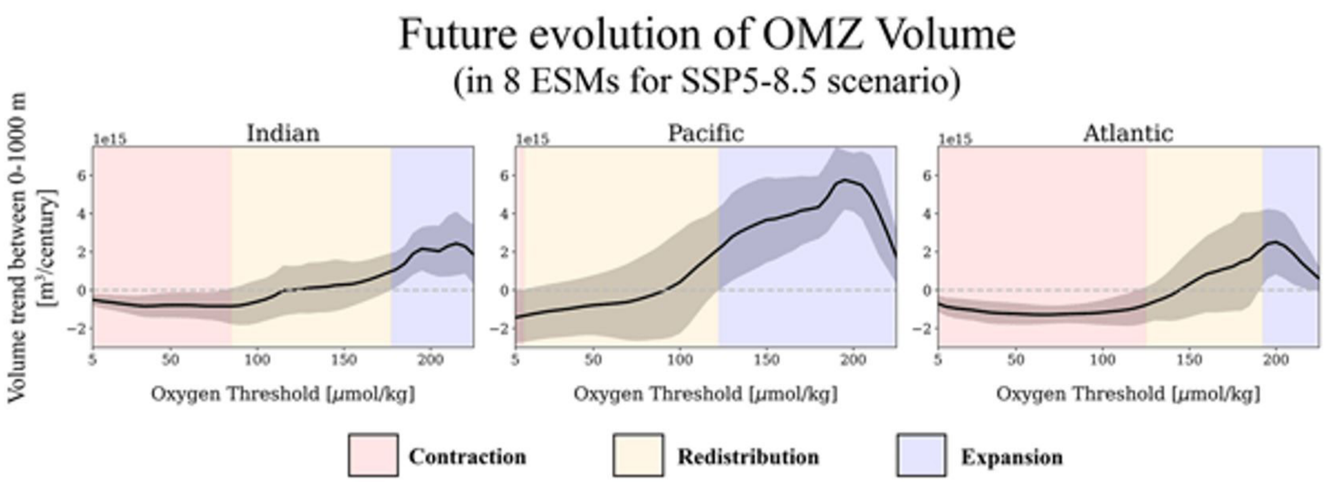
Research Highlight

The ocean has lost dissolved oxygen (O_2) in response to global warming in the past 50 years. A serious threat of this systematic ocean deoxygenation is the expansion of tropical oxygen minimum zones located in the subsurface ocean. Equally threatening is the more frequent occurrence of coastal dead zones where human pollution originating from the land, such as fertilizers, urbanization, wastewater, etc., reinforces the depletion of oxygen (e.g., Resplandy, 2018).

The first project focused on explaining the unexpected and counter-intuitive weak change in oxygen (and even increase in some places) observed in parts of the Atlantic Ocean in the past 50 years. The researchers showed that this pattern can be explained by the amplification of the hydrological cycle, a response to climate change. Using a series of Earth system model experiments, they found that the hydrological effect increases the supply of oxygen in "salty-get-saltier" subtropical waters, countering the oxygen loss tied to warming. At the same time, this reduced the supply of oxygen in "fresh-get-fresher" deep waters, reinforcing the oxygen loss tied to warming. This work reveals that long overlooked indirect effects of warming, through hydrological changes, can substantially influence ocean de-oxygenation patterns.

The second project expanded on work published in 2022 on the Pacific Ocean oxygen minimum zone (Busecke et al., 2022). This work showed that three regimes control the future of the oxygen minimum zone under climate change in all basins (Figure 11.1). The three regimes include: the expansion regime of "low oxygenated waters;" the contraction regime of the "core waters" (lowest oxygen levels within the oxygen minimum zone); and in-between, a transition regime with spatial redistributions but little change in volume. This three-regime view of oxygen minimum zones is crucial to assess impacts. For example, the expansion of "low oxygenated waters," which delimits the optimum habitat of numerous marine species, could impact marine ecosystems and ecosystem services. Likewise, the contracting "core waters" could limit the production of oceanic nitrous oxide.

Figure 11.1.
Future of evolution of OMZ Volume (in eight Earth system models for the high emission SSP5-8.5 scenario) - Multi-model mean thermocline OMZ volume trends (above 1,000 m, 2015–2100) as a function of oxygen threshold for the tropical (a) Indian, (b) Pacific, and (c) Atlantic oceans.



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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

At a Glance

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 (CO_2) and other GHGs. The overall goal is to better constrain mitigation pathways that would stabilize the climate.

Research Highlight

The initial phase of evaluation of a new Earth System Model (ESM) usually occurs in pre-industrial (PI) configurations. This refers to climate conditions corresponding to the 1850s, before the onset of the Industrial Revolution and the rapid increase in anthropogenic GHG emissions. It usually takes several hundreds to thousands of simulated years in PI configurations to evaluate and revise an ESM code to establish model fidelity and produce a stable, non-drifting physical climate and carbon cycle. In the last Coupled Climate Model Intercomparison project, phase 6 (CMIP6), the stability of the simulated carbon cycle required a long-term CO_2 flux between land, ocean, and atmosphere in the CO_2 emission-driven PI simulations to be less than 0.1 Petagram of carbon per year (Pg C/year). GFDL conducted dozens of experiments, including an historical 1850 to 2014 experiment. These were completed in coordination with other international and national centers participating in CMIP6. GFDL also shared Petabytes of data with the broader scientific community. It is important to understand that GFDL does not tune its historical simulations to observed historical records.

Last year, Shevliakova and her colleagues at NOAA/GFDL and CMI scientists concluded an in-depth evaluation of the historical trends in the land surface climate from 1850 to 2014 simulated by the NOAA/GFDL ESM4.1 model. The evaluation focused on the fidelity of its land component, Land Model version 4.1 (LM4.1). The team also explored ways to improve hydrological, ecological, and biogeochemical processes for the next generation of GFDL ESMs. Features of LM4.1 include advanced vegetation dynamics, plant hydraulics, multi-layer canopy energy and moisture exchanges, daily fire, land use representation, and dynamic atmospheric dust coupling. These features vastly improved mean climate and variability compared to previous generations of the GFDL models (Figure 12.1). Shevliakova et al. (2024) documented the results of the analysis of land surface climate in a recently accepted manuscript.

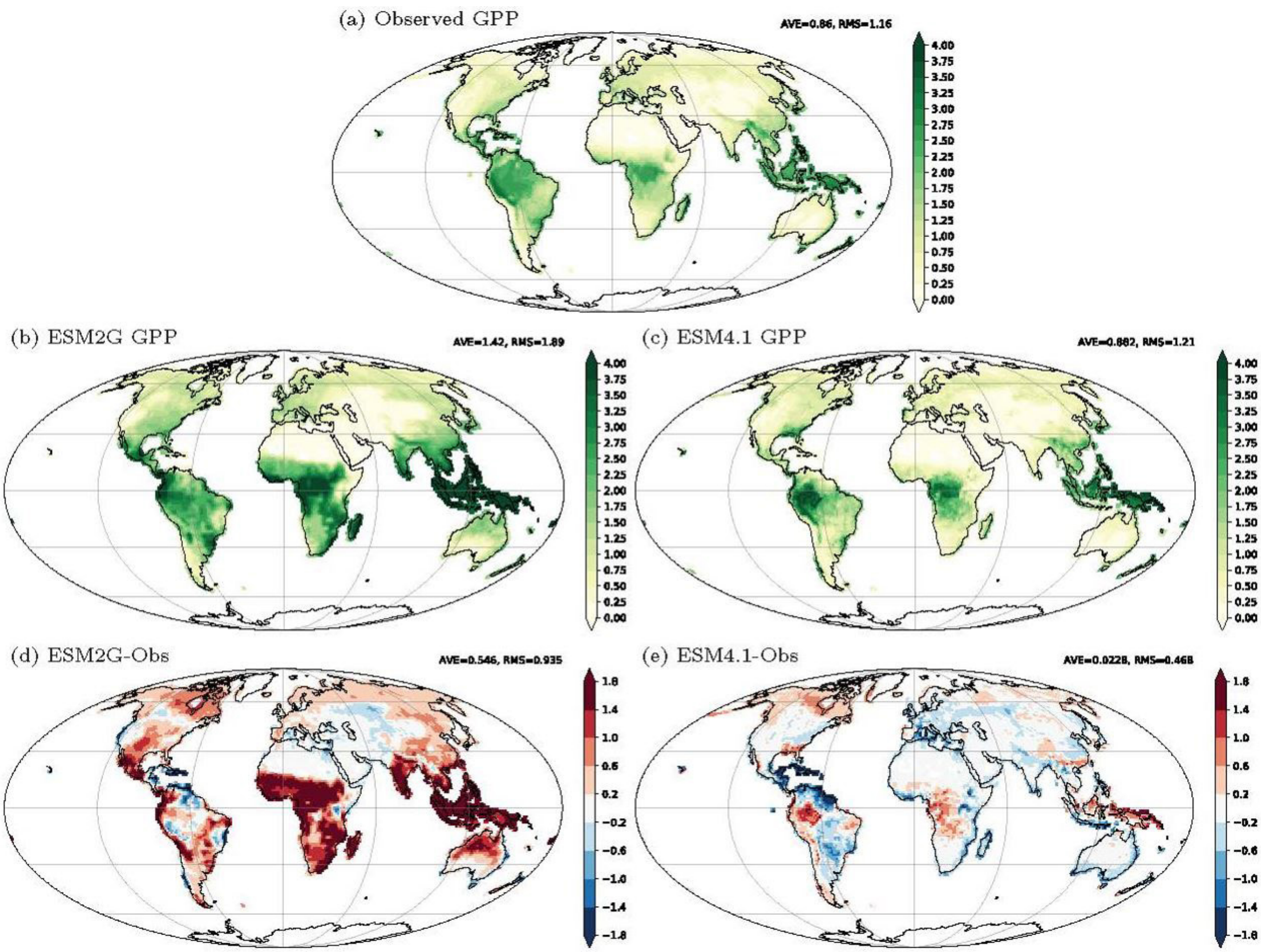

Figure 12.1. Comparison of the reconstructed Gross Primary Production (GPP, the measure of the gross carbon uptake by vegetation) and the simulations of GPP by the two generations of the GFDL Earth System models, ESM2G (used in CMIP5) and ESM4.1 (used in CMIP6) (Shevliakova et al., 2024).

In preparation for the CMIP7 and to enable comprehensive treatment of hydrological and biogeochemical exchanges, Sergey Malyshev, in collaboration with GFDL scientists and AOS postdoctoral fellows, led several improvements of the LM4.1 representation of land-atmosphere exchanges for water, energy, and chemical tracers. These included turbulent exchanges of moisture and energy between the ground and the canopy air. It also included a parameterization enabling a more faithful representation of the interaction between the planetary surface and the atmosphere.

In addition, the AOS research scholar and CMI contributor Enrico Zorzetto, in collaboration with GFDL scientists Malyshev, Ginoux, and Shevliakova, implemented a new Global Land-Atmosphere Snow Scheme (GLASS). This model accounts for the effects of snow aging and impurities such as dust and carbon deposits from fire on snow albedo. The team also initiated two new projects focused on improving the spatial distribution of fires in the orography-aware (meaning taking topography into consideration) version of LM4.1 and linking damages and tree mortality to drought conditions. This will be used to explore linkages between fire, hydrological cycles and vegetation dynamics. The ongoing coordinated improvements to hydrological and carbon cycling treatments in LM4.1 will reduce uncertainty in the prediction and projections of land carbon stocks, including their vulnerability to changing climate and extremes. Significant changes in land carbon stocks would impact the world's remaining budget for fossil fuel emissions.

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Interaction Between Climate Change, the Carbon Cycle, and Biodiversity

PRINCIPAL INVESTIGATOR: STEPHEN PACALA

At a Glance

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

Summer 2023. Matteo Detto and Hannes De Deurwaerder went on a field campaign in the Smoky Mountains (TN) to measure leaf gas exchange of the dominant canopy trees. The pictures show vegetation and wildlife of the Great Smoky Mountains National Park and the operation of the IRGA gas analyzers (LiCOR-6400) in the NEON facility (Photos credit: Hannes De Deurwaerder) 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.

Research Highlight

Biodiversity has a large impact on climate, two bodies of scientific work imply. First, experiments and measurements show that carbon uptake and carbon storage substantially increase with diversity (Figure 13.1, Tilman et al., 2014). Second, the diversity of plant species in a basin strongly affects watershed-scale evapotranspiration in natural ecosystems (Figure 13.2, Anderegg et al., 2018).

Figure 13.1.
Increasing species number increases biomass in a greenhouse experiment (Naeem et al., 1995; Tilman et al., 2014).

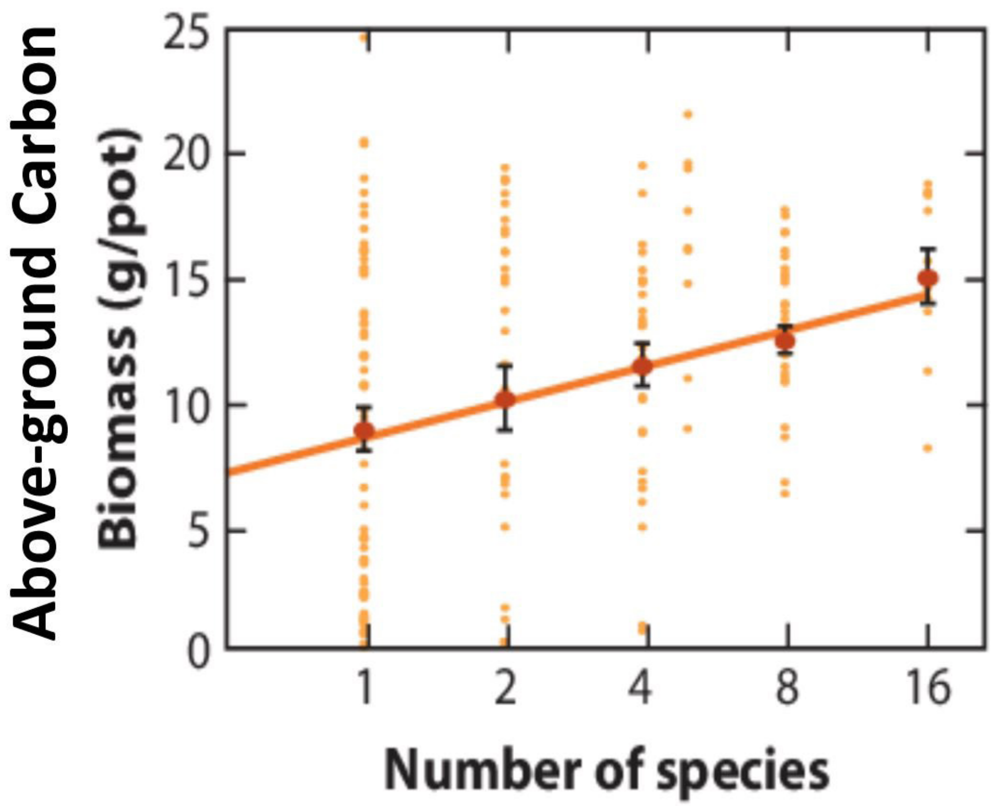
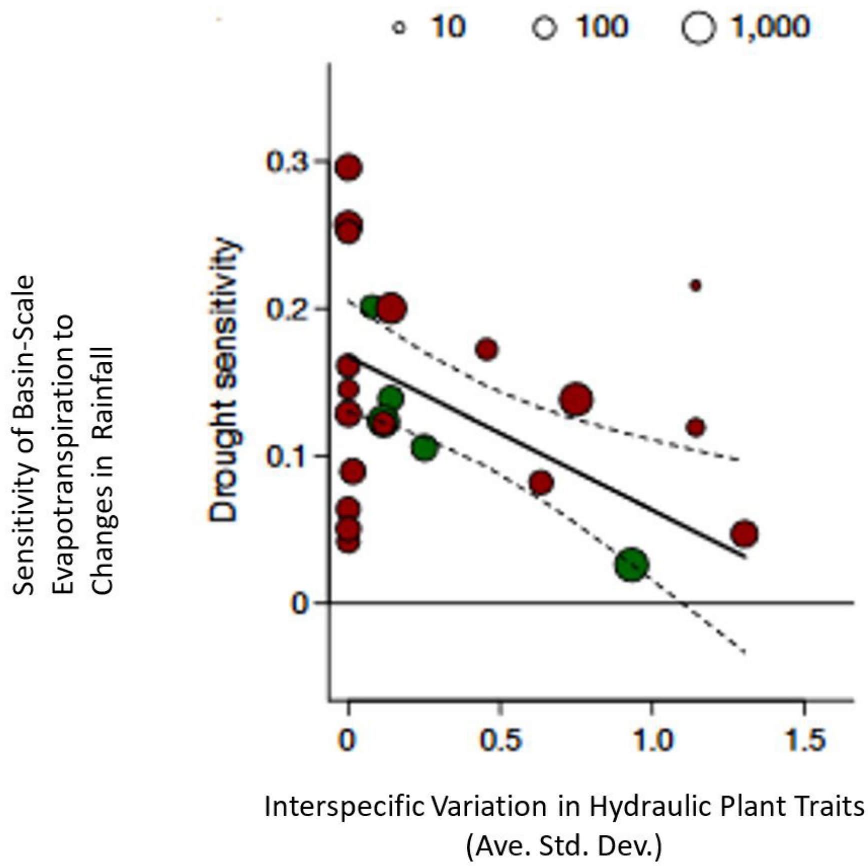
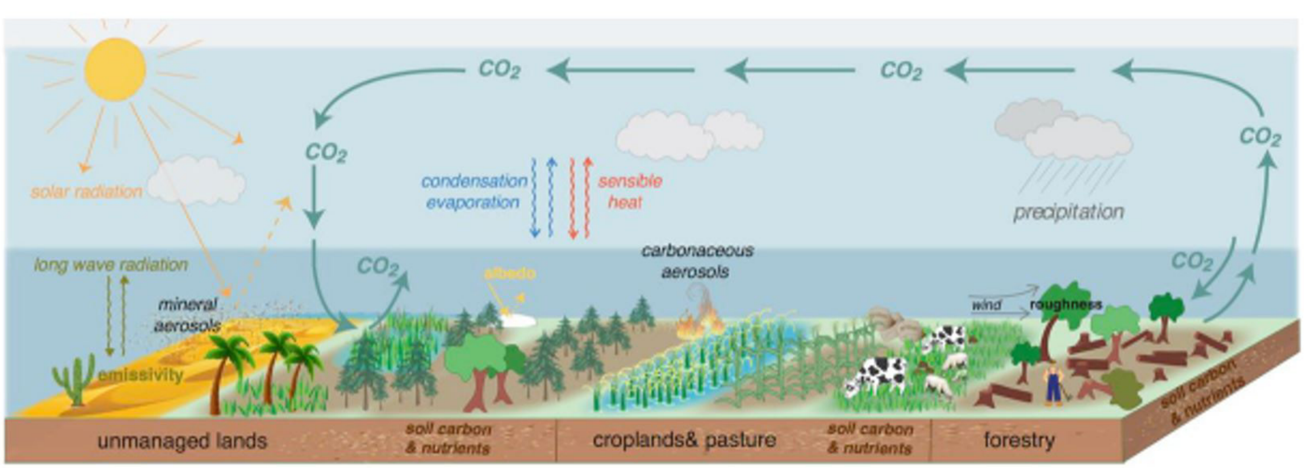


Figure 13.2.
Ecosystem sensitivity to drought as a function of community variation in hydraulic safety margin (Anderegg et al., 2018).



These effects are very large – note the changes of 100% in Figure 13.1. Nonetheless, Earth System models do not yet include them, in part because the mechanisms that maintain the diversity are not understood. The Pacala lab has focused for the last several years on building an Earth System model in which species diversity in traits that affect climate is maintained for the right reasons. These efforts use simplifications of the land component of the NOAA GFDL Earth System model (LM4), which the Pacala lab produced with Elena Shevliakova and Sergey Malyshev of GFDL (Shevliakova et al., 2024; Figure 13.3). Published examples include Detto et al. (2021) in *Ecological Monographs*, and Levine et al. (2022) in *Ecology Letters*, with another four in various stages of review.

Figure 13.3.
Schematic of land surface processes (e.g. dynamic vegetation competition, land use) and land-atmosphere interactions including radiative, hydrological, CO_2, dust and other aerosol fluxes in GFDL's LM4.1 land model (Shevliakova et al., 2024).



These papers show that the processes already present in LM4 will maintain very high levels of species diversity in traits that affect climate, which was a surprise the researchers did not understand. In the past year, the work showed that all these models have the same unexpected underlying mechanism that maintains diversity. This will greatly facilitate the development of operational climate-biodiversity models. The mechanism that maintains diversity, though widely criticized as unrealistic, has been in the ecological literature for more than 50 years (Levins and Culver, 1971) and is known as the "competition-colonization model." Its emergence was unexpected because the mechanism in the competition-colonization model was not built into the researchers' models, but rather emerged by a nonobvious path directly from the physiological realism. The work is relevant to bp, because it will lead directly to better understanding of the resilience and longevity of the terrestrial carbon sink, which is a primary determinant of humanity's remaining emissions budget.

Additionally, two other large projects were led by Pacala in the past year. Neither was funded by the CMI, but both are relevant. First, Pacala chaired a committee of the National Academies of Science Engineering and Medicine, which released in October 2023 a more than 600-page policy manual for implementation of the Inflation Reduction Act and the Infrastructure Investment and Jobs Act. Since its release, Pacala has given between 50 and 100 briefings on this work, mostly to federal agencies. Second, Pacala chaired, with economist and Stanford Business School Dean Jon Levin, a study and report on how to safeguard the U.S. population and economy against climate-change-enhanced extreme weather. This is intended for the President and was released in April 2023. One of the primary recommendations in this report is for a new effort to produce much better and more geographically granular estimates of the probabilities of extreme weather over the next 25 years. This is now underway using Infrastructure Investment and Jobs Act (IIJA) funding.

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