Tropical forest canopy in Mato Grosso, Brazil
Photo provided by Dr. Paulo Brando

2024 ANNUAL REPORT

Yale *Center for Natural Carbon Capture*

Table of CONTENTS

EXECUTIVE SUMMARY

The Yale Center for Natural Carbon Capture (YCNCC) was established in 2021 with a transformative gift from FedEx – followed by significant subsequent support from Boeing and Southwest Airlines – to explore the fundamental and applied science relating to how natural processes can be enhanced to create safe, effective, and scalable methods to reduce atmospheric concentrations of greenhouse gasses.

Research represents the heart of the Center's work. In addition to advancing the science relating to natural carbon capture, YCNCC is committed to supporting the development of the next generation of researchers, as well as public engagement to communicate and extend the best available science to practitioners, policymakers, and corporate sustainability leaders.

Fiscal year 2024 (FY24) was a period of accelerating impact across the Center's three areas of focus: Ecosystem Capture, Geological and Ocean Capture, and Industrial Carbon Utilization. This Annual Report details the Center's efforts and activities over the past year, including:

MAJOR ACCOMPLISHMENTS

- YCNCC scientists secured $30 million in new grant funding from a diverse range of sources, including the U.S. Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and others.

- A number of YCNCC-connected startups made significant progress with the commercialization of their carbon management technologies:
    - CREW Carbon, Ebb Carbon, Lithos Carbon, and Mati Carbon advanced to the semi-final round of the DOE Carbon Dioxide Removal (CDR) Pilot Purchase Prize – the first U.S. Government initiative to directly procure carbon removal.
    - Ebb Carbon, Lithos Carbon, and Mati Carbon were named finalists for the $100 million XPRIZE Carbon Removal competition.
    - Lithos Carbon secured the world's first offtake purchase agreement for enhanced rock weathering (ERW) in the amount of $57.1 million from the Frontier Climate Fund.
    - Two YCNCC-connected startups raised seed funding: $5.3 million for CREW Carbon, and $4.5 million for Oxylus Energy.

- YCNCC is welcoming two new hires: Dr. David Kwabi, who will join the Department of Chemical & Environmental Engineering and the YCNCC Scientific Leadership team in January 2025; and Toby Bryce, who joined in June 2024 as Managing Director to lead the Center's administration, communications, development, and external affairs.

- YCNCC held its second annual Spring Symposium, which focused on the potential for marine carbon dioxide removal (mCDR) to play an integral role in mitigating the climate crisis. Over two days, attendees heard from preeminent scientists and researchers, high-level government representatives, and a number of companies and organizations working to deploy, support, and advance mCDR solutions, including: Google, Microsoft, [C]Worthy, Isometric, Banyu Carbon, Calcarea, Hourglass Climate, Aquatic Labs, Planetary Technologies, Captura, Equatic, Ebb Carbon, Carbon180, and Oceans Visions.

EXECUTIVE SUMMARY

RESEARCH HIGHLIGHTS

- YCNCC researchers published a total of 47 scientific articles over the past year in peer-reviewed journals. These publications detailed results of YCNCC-funded research on ecosystem, geological, ocean, and industrial carbon capture, including studies of regenerative agriculture and soil organic carbon; forest degradation in the Brazilian Amazon; methane fluxes in terrestrial ecosystems; agronomic co-benefits of enhanced weathering; the role of ocean mesoscale variability in air-sea carbon dioxide (CO_2) exchange; electrochemical ocean alkalinity enhancement; plasma electrolysis for CO_2 conversion and green ammonia; and electro-reduction of carbon oxides into methanol.

- The Yale Applied Science Synthesis Program (YASSP), a major initiative of YCNCC, works with for-profit and not-for-profit partners seeking to make decisions about sustainable land management practices and produces open and transparent public-good research, with the goal of promoting the widespread application and development of these findings. This year, the YASSP team participated in a number of national summits, expert working groups, and hosted technical workshops to advocate for more rigorous carbon crediting protocols in voluntary and compliance markets. Most notably, YASSP researchers co-authored the U.S. DOE 'Roads to Removal' report, which lays out pathways for the US to remove at least 1 billion tonnes of carbon dioxide (CO_2) per year from the atmosphere by 2050.

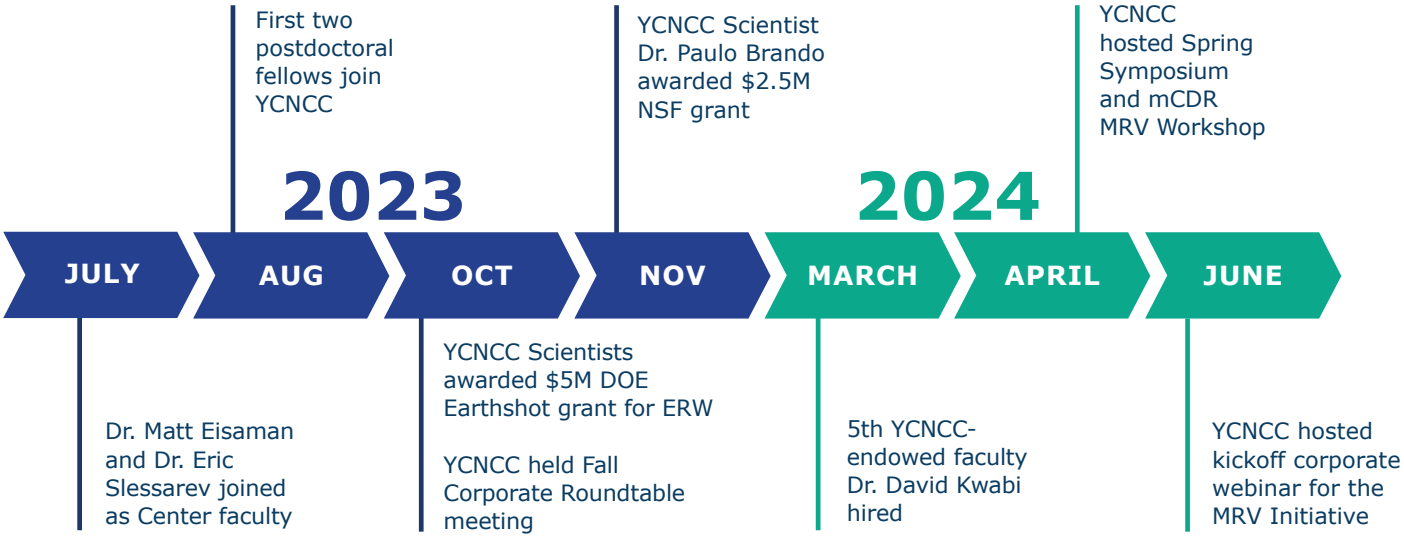
- YCNCC scientists are advancing a number of key initiatives relating to ERW, a carbon removal method that seeks to leverage the natural weathering of rocks to capture and sequester CO_2. These include: collaborating with Microsoft, FedEx, and the Frontier Climate Fund to publish recommendations for ERW best practices; partnering with Microsoft to conduct an academic evaluation of data generated from ERW projects sponsored by the company; and securing over $10 million in grants and gifts from the USDA, Google, the Grantham Foundation, and the U.S. DOE.

- YCNCC scientists are studying mCDR approaches that focus on increasing alkalinity in seawater, which enables the ocean to pull additional CO_2 from the air and store it for ~10,000 years. This year, YCNCC scientists presented mCDR research results at major conferences, including the American Geophysical Union (AGU) Fall Meeting, and hosted a well-attended symposium on mCDR.

- YCNCC scientists are working across the globe to advance the understanding of the carbon sequestration potential of blue carbon ecosystems, such as salt marshes, mangroves, and seagrass beds. To this end, YCNCC researchers are engaged with a number of key blue carbon initiatives, including developing and receiving a provisional patent for an affordable tool to measure key aspects of blue carbon sequestration potential in the field.

- YCNCC researchers continue to develop new innovations relating to industrial carbon utilization across a range of potential applications, including converting CO_2 to plastics, chemicals, and fuels.

MAJOR MILESTONES



PREFACE

Over the last year we have witnessed firsthand the increasing impacts of climate change: from record-breaking heat to wildfires to floods and other extreme weather events. These global events are not unexpected – scientists have been warning about them for decades – but they are shocking in their scope, regularity, and intensity.

At the same time, we have never seen more global momentum to implement solutions to combat climate change. Governments around the world are implementing policy, and committing billions of dollars in funding, to advance these technologies and jumpstart the markets that will enable them to mature and scale. In the private sector, there are nearly 900 companies working to remove CO_2 from the atmosphere – more than at any time in history. Forward-thinking corporations are stepping up to make large, unprecedented purchases of carbon removal to meet their own net zero goals, as well as to stimulate a growing industry that is essential if we're to meet the goals of the Paris Agreement, and remain below warming thresholds that could bring irreversible global impacts. In this context, the work by YCNCC scientists to spur innovation and inform policy and management practices with rigorous and cutting-edge scientific research has never been more important.

YCNCC researchers are playing an integral and active role in developing and advancing many of the major approaches to carbon removal, as well as developing the frameworks and academic underpinnings that will establish confidence in their effectiveness. Teams of Yale scientists are working across disciplines to tap into the vast carbon storage capacity of the world's oceans and forests, protect and restore coastal ecosystems, harness natural processes like photosynthesis and rock weathering, and turn already-emitted CO_2 into valuable products – all with the goal of progressing toward removing billions of tonnes of CO_2 from Earth's atmosphere in the coming decades.

It's with this backdrop that we present YCNCC's 2024 Annual Report. This report underscores the importance of integrating natural carbon capture methods with innovative solutions to address climate change. The Center's work to protect and enhance ecosystems, advance geological and oceanic carbon sequestration, and develop sustainable industrial carbon utilization processes is vital for achieving significant, scalable reductions in atmospheric concentrations of CO_2 and other greenhouse gasses. These efforts not only contribute to global climate mitigation goals but also provide critical co-benefits for biodiversity, ecosystems, agriculture, and sustainable development. As YCNCC continues to lead in natural carbon capture research, the Center's efforts will be instrumental in shaping effective, holistic strategies for a resilient and sustainable future.

YCNCC Faculty Directors
Dr. Liza Comita and
Dr. David Bercovici

Photo provided by Yale News

RESEARCH UPDATES

Research is the foundation and core of YCNCC's mission. Over the course of FY24, the Center's scientists have continued to advance groundbreaking research across the Center's three areas of focus – Ecosystem Capture, Geological and Ocean Capture, and Industrial Carbon Utilization. In FY24, YCNCC provided funds for over twenty research projects, including substantial grants for our major initiatives as well as seed grants to foster new ideas and provide critical support for Yale scientists to gather initial data to assess project feasibility and make them competitive for larger, external grants. YCNCC has also continued to advance two major research-related infrastructure projects – the establishment of a coastal marine station to support the Center's mCDR work, and renovated space in Osborn Memorial Laboratories to house YCNCC faculty, postdoctoral researchers, and staff. A detailed update on these infrastructure projects can be found in Appendix D.

This investment in research has paid off, resulting in 47 peer-reviewed articles published in academic journals, over $30 million of new grant funding to continue YCNCC-sponsored research, and partnerships with dozens of external collaborators. Additionally, YCNCC-connected startups made significant progress over the course of FY24 – advancing in both the DOE CDR Pilot Purchase Prize and XPRIZE competitions; securing a $57.1 million offtake purchase commitment for CDR credits; and raising nearly $10 million in seed funding. Detailed updates from YCNCC-connected startups can be found in Appendix E.

Below we highlight several major areas of research conducted by YCNCC in FY24. Please see Appendix A for detailed reports of all YCNCC funded research projects.

PUBLICATIONS

Scientific Publications

8 Industrial Carbon Utilization

18 Ecological and Biological Capture

21 Geological and Ocean Capture

$30M

Amount of funding obtained for follow up studies

External collaborators

30 Academia

3 Private Companies

14 Nonprofit Orgs

ECOSYSTEM CAPTURE

Yale Applied Science Synthesis Program

Terrestrial ecosystems like forests, agricultural lands, grasslands, and shrublands play a critical role in capturing and storing large amounts of carbon dioxide. Enhancing the capture and storage of carbon within these ecosystems, through preservation, restoration and management practices, is a proven strategy for reducing atmospheric carbon levels and mitigating the impacts of climate change. However, evaluating and understanding the carbon removal potential of these systems relies on a number of variables – everything from land use policies to soil sampling protocols to the impact of animal migration patterns.

YCNCC researchers are working to explore different terrestrial removal pathways, as well as the less understood variables that may impact their effectiveness. Through on-the-ground research projects, the evaluation of different modeling approaches, remote sensing using drone and satellite technology, and the development of novel tools to measure impact and effectiveness, YCNCC researchers are contributing meaningful scientific outputs that will help guide the development of these potentially large-scale climate mitigation strategies.

The Yale Applied Science Synthesis Program (YASSP), a major initiative of YCNCC led by Scientific Leadership Team members Dr. Mark Bradford and Dr. Sara Kuebbing, connects academic researchers, policymakers, and land management professionals to answer questions about how land management decisions affect the services provided by forests, croplands, wetlands, rangelands, and grasslands. With widespread interest in 'climate-smart' forestry and agriculture for climate mitigation and adaptation purposes, YASSP is focusing its work in forested and agroecosystems in tropical and temperate systems. The initiative aims to:

1) Synthesize and model expected carbon gains in response to ecosystem management changes

2) Review current methods and approaches for measuring carbon fluxes in response to management decisions

3) Convene and engage with land managers and policymakers who are pursuing carbon-based ecosystem management projects to bring the best available science to land management activities

YASSP works with for-profit and not-for-profit partners seeking to make decisions about sustainable land management practices and produces open and transparent public-good research, with the goal of promoting the widespread application and development of these findings. YASSP works to maximize ecosystem benefits provided by land resources, such as carbon storage, sustainable food production, and biodiversity.

MAJOR FY24 ACCOMPLISHMENTS INCLUDE:

- YASSP researchers co-authored the U.S. DOE 'Roads to Removal' report, which lays out pathways for the US to remove at least 1 billion tonnes of CO2 from the atmosphere per year by 2050.

- A major limitation in scaling improved management practices for increasing carbon storage lies in the soil research community's lack of agreement on measuring and confirming soil carbon gains. Recent findings by YASSP researchers have revealed a scarcity of empirical evidence supporting claims of reliably measuring soil carbon increases. While some scientists argue that it is infeasible to empirically measure soil carbon changes, initial work by YASSP researchers have countered this argument, demonstrating that thoughtful experimental designs could reliably estimate soil carbon gains and provide guidelines for conducting rigorous soil sampling campaigns.

RESEARCH UPDATES

- YASSP researchers have also worked to improve MRV protocols for carbon sequestration in soil – which is hindered by the limited availability of data – by providing a synthetic dataset of U.S. croplands available for public use.
- YASSP researchers highlighted how structural differences in MRV protocols impact the number of soil carbon credits attributed to specific projects, further emphasizing the need for continued research in additionality and uncertainty assessments to enhance confidence in MRV protocols.
- While there is widespread acknowledgment of forests' potential for climate mitigation and carbon capture, there's also widespread disagreement on the best forest management options and effective carbon tracking programs. YASSP research demonstrated how tailoring forest management to regional socioeconomic and environmental conditions and incorporating disturbance regimes can address this discord, leading to net forest carbon gains with many additional biodiversity, economic, and human health benefits.
- YASSP researchers participated in a number of national summits, with the goal of reconciling competing narratives about forest management.
- The team also advocated for more rigorous carbon crediting protocols in voluntary and compliance markets through participation in expert working groups, as well as hosted technical workshops that bring together academic and applied researchers.

Tropical agroecosystem landscape

Photo provided by YASSP

Blue Carbon Initiative

Blue carbon is a climate mitigation solution that leverages the natural carbon capture and storage potential of coastal ecosystems, such as salt marshes, mangroves, and seagrass beds. These ecosystems serve as critical habitat for a wide range of coastal and marine organisms, including economically important commercial fisheries, and can help stabilize shorelines and protect coastal communities from storm damage. In addition to these vital ecosystem services and resiliency functions, blue carbon represents an opportunity for carbon sequestration because these systems naturally capture carbon dioxide from the atmosphere and store it in underlying marine sediments. Processes within these systems can also release alkalinity into the ocean, which can capture and sequester atmospheric carbon dioxide for thousands of years, further enhancing the carbon removal potential of blue carbon.

Despite the climate mitigation potential of blue carbon ecosystems, they are incredibly vulnerable to climate change itself – through rising sea levels and pollution – as well as human development along coastal areas. Nearly 67 percent of mangroves, 35 percent of tidal marshes, and 29 percent of seagrass meadows have already been destroyed, and it is estimated that upwards of 2.4 million acres of blue carbon ecosystems are lost each year – potentially releasing up to a billion tonnes of carbon dioxide into the atmosphere. Protecting, restoring, and enhancing these ecosystems represents a natural carbon sequestration solution that can also provide substantial co-benefits, including enhanced productivity of fisheries, local mitigation of ocean acidification, pollutant removal, and storm protection.

YCNCC scientists are working across the globe to advance the understanding of the carbon sequestration potential of blue carbon ecosystems, with the goal of supporting and informing efforts to protect, restore, and enhance these vital systems for their climate regulating impacts. YCNCC's Blue Carbon Project, led by YCNCC Scientific Leadership Team member and Yale School of Environment Professor and Associate Dean Dr. Peter Raymond, aims to investigate how carbon flows within coastal systems, including mangrove forests, salt marshes, and seagrass meadows. The project seeks to understand the amount of carbon and other greenhouse gasses stored in different components of these ecosystems and for how long.

This research is significant because these systems are increasingly impacted by human activities, such as coastal development, and climate change itself, through extreme weather events. Despite their importance in providing economic benefits and services such as storm surge protection, water filtration, and support for fisheries, scientists still lack a comprehensive understanding of carbon dynamics and storage within these ecosystems. This project seeks to fill this knowledge gap and contribute to a better understanding of coastal ecosystems' role in carbon sequestration and climate change mitigation.

RESEARCH UPDATES

KEY FY24 MILESTONES INCLUDE:

- The team worked in Florida and Massachusetts to measure alkalinity produced by blue carbon ecosystems – the process by which carbon from blue carbon ecosystems is flushed into the sea and stored for long periods of time as carbonates. This feature of blue carbon is not well studied but is critical to understanding total carbon sequestration capacity. Based on data collected to date, and further data to be collected in the future, the team is modeling this key component to test how it will impact the total carbon sequestration rates of blue carbon remediation and restoration projects.

- The team is also developing an affordable tool to measure alkalinity in the field. The instrument, which is made of multiple pumps, valves, and a sophisticated electronics system, has undergone laboratory and initial field tests and has received a provisional patent. A $30,000 grant from the U.S. Geological Survey (USGS) has been secured to further develop this novel instrument.

Seagrass in the Pacific Ocean

Photo provided by Dr. Anitra Thorhaug

GEOLOGICAL AND OCEAN CAPTURE

Enhanced Rock Weathering Initiative

Enhanced rock weathering (ERW) is a highly promising strategy for durable carbon removal via agricultural lands that seeks to accelerate the natural weathering of silicate rocks by rainfall, the hydrological cycle, and river systems. Weathered rocks and minerals react with carbon dioxide dissolved in water, and store it as durable carbonates in soil and ocean sediments. These processes play a crucial role in regulating the level of carbon dioxide in the atmosphere and maintaining the stability of the climate. In nature, however, weathering occurs slowly, over geological timescales of thousands to millions of years.

Accelerating these natural processes has the potential to remove harmful greenhouse gasses on timescales that will help address climate change more quickly. ERW strategies involve spreading finely ground minerals – most often basalt – over large areas of land to speed up the chemical reactions that capture CO_2. By increasing the surface area of rocks in contact with the atmosphere, this strategy allows for greater amounts of CO_2 to be captured directly from the atmosphere. Once removed, much of this carbon is washed into the ocean and stored as bicarbonate – a safe, stable and permanent storage pathway that also reduces ocean acidity, and thus has co-benefits for coral reefs and marine ecosystems. ERW can also benefit crop yields by releasing nutrients and neutralizing acid in soils, providing a more favorable environment for plant growth.

Led by YCNCC Scientific Leadership Team members Dr. Noah Planavsky, Dr. Peter Raymond, and Dr. James Saiers, this YCNCC initiative is exploring multiple aspects of ERW through laboratory work, field studies, and modeling, with the goal of more accurately understanding the carbon removal potential of this strategy and helping to increase the effectiveness of interventions

This project is exploring the potential of CO_2 removal in agricultural lands and developing methods to track and quantify ERW strategies to ensure long-lasting CO_2 removal. Researchers are conducting field trials where ground-up minerals are added to fields growing different crops. They will then measure carbon uptake rates via plant productivity, soil carbon storage, and downstream transport through watersheds to the ocean. Laboratory analyses and a review of existing scientific literature will complement the field trials.

RECENT ACCOMPLISHMENTS:

- YCNCC scientists have demonstrated carbon capture through ERW at a greater than 10-tonne scale over multiple years and conducted an exploration of how enhanced weathering affects soil structure, moisture retention, and drought resistance.
- Based on its work to date, the YCNCC ERW team is collaborating with Microsoft, FedEx, and Frontier Climate Fund to produce recommendations for ERW best practices. The team is also working on a project with Microsoft to conduct an academic evaluation of specific ERW efforts.
- To date, the team has secured over $10 million in ERW grants and gifts from USDA, Google, the Grantham Foundation, and DOE.

RESEARCH UPDATES

- The team conducted a whole-watershed application of 450 tonnes of crushed basalt on pasture and hayfield in Vermont. The basalt application was completed in June 2023. Hydrological, geochemical, and biological measurements were initiated in 2022 following installation of a groundwater-monitoring array, automated surface-water samplers, and streamflow instrumentation. Increases in stream water alkalinity demonstrating CO_2 removal by basalt weathering have been observed and are currently being quantified.

- The team continued development of instrumentation for measuring CO_2 removal by ERW, with a newly developed AutoLysimeter. This instrument enables accurate determination of soil-water and weathering-product fluxes over a range of soil-moisture conditions. It can be rapidly deployed at low cost and with minimal site disturbance.

- The team partnered with Connecticut Land Trusts and identified several Land Trusts interested in hosting ERW field trials. Site selection will begin in fall 2024 with ERW trials beginning in spring 2025.

Basalt spreading at a YCNCC ERW field trial in Vermont

Photo provided by Dr. James Saiers

Marine CDR Initiative

While there are a number of proposed strategies to remove carbon dioxide from the atmosphere, one of the most promising approaches seeks to leverage the natural attributes of the ocean. The ocean is a natural ally in carbon dioxide removal, playing a key role in the Earth's primary mechanism for controlling carbon dioxide concentrations in the atmosphere. Since the Industrial Revolution alone, the ocean has absorbed around thirty percent of all carbon dioxide emitted on Earth. Covering over seventy percent of Earth's surface, the ocean represents the largest sink available for capturing carbon dioxide from the atmosphere. Like forests, the world ocean draws down nearly 100 billion tonnes of carbon per year, and returns a bit less; even a small shift in the balance between drawdown and return would have a huge impact. Moreover, the pool of carbon dissolved durably in the ocean (as "dissolved inorganic carbon") is twenty times the size of the entire biospheric carbon mass; thus sequestering anthropogenic carbon in the oceans would add a negligible amount to the ocean carbon reservoir. The natural ability to draw down and store carbon dioxide makes the ocean a potential game-changer in the climate crisis.

The Marine CDR Initiative, led by YCNCC Scientific Leadership Team members Dr. Matthew Eisaman and Dr. Mary-Louise Timmermans, is studying mCDR approaches that focus on the process of ocean alkalinity enhancement (OAE). Increasing alkalinity in seawater enables the ocean to pull additional carbon dioxide from the air and store it as bicarbonate ions – a natural form of carbon storage that is stable for around 10,000 years. While more research is needed into its efficacy, verification strategies, and safety, OAE holds the promise to draw down massive amounts of carbon dioxide with minimal impact on the ocean.

YCNCC is working to address many of the critical questions around the safety, efficacy, and reliability of OAE approaches, including:

- The behavior of alkaline particles. How do particles behave in dynamic marine environments? What are the relevant fluid dynamics? How do ocean currents, stratification, and particle size impact carbon dioxide drawdown?
- The dispersion of alkaline solutions. How do alkaline solutions disperse in the ocean under various conditions and settings?
- Biological impacts. What is the impact of mCDR on specific marine species? How can we define safe operational bounds with regards to health and survival and assess the potential benefits to economically important species like shellfish?
- Advancing MRV tools. What are the fit-for-purpose ocean models, sensors, and unique methodologies that will increase certainty and confidence in these technologies' ability to make a meaningful impact on climate change?

RESEARCH UPDATES

KEY FY24 ACCOMPLISHMENTS:

- By investigating the variability and drivers of carbon dioxide exchange between the atmosphere and ocean on a global scale, the team identified a new variable that impacts this exchange. While previous studies have suggested the exchange may be governed by one of two main ocean parameters – sea surface temperature or dissolved inorganic carbon – the team has discovered that seasonally varying factors can be associated with anomalously high carbon dioxide uptake rates. The research has also shown that the orientation of small-scale ocean motions, such as strong eddying motions and other energetic currents, in relation to the background distribution of carbon in the ocean can lead to a significant gain or loss of CO_2 captured at the regional level. These findings have implications for understanding the ocean's ability to absorb and store carbon in different regions, and how that might change in the future based on a number of variables.

- The team has also made progress to better understand and quantify the carbon dioxide removal potential of adding milled mineral particles to the ocean. The method's success depends on how long the particles stay in the surface ocean to dissolve, which is influenced by how fast they settle. Typically, settling rates are measured under still conditions. However, the team's research found that in a moving, layered ocean setting, this settling rate can vary significantly, in some cases causing particles to settle up to ten times faster. These findings highlight the need to consider different marine conditions to optimize carbon removal strategies.

Coastal estuarine system

Photo provided by Eisaman Lab

Industrial Carbon Utilization

Carbon dioxide is one of the most wasted substances of all time – with human activities having released an estimated 1.5–2.4 trillion tonnes of it into the atmosphere since the industrial revolution. Finding innovative ways to harness this waste and turn it into valuable products presents an opportunity to not only contribute meaningful carbon removal, but also to reduce the carbon footprint of manufacturing certain products – combining two of the largest levers for addressing climate change: carbon removal and decarbonization.

There are various ways to use captured carbon dioxide in industrial applications, including using it as a feedstock to produce chemicals, fuels, and building materials like concrete or plastics. Multiple YCNCC researchers, including YCNCC Scientific Leadership team member Dr. Nilay Hazari and affiliated faculty Dr. Hailiang Wang and Dr. Lea Winter, are advancing the field of industrial carbon utilization across a range of potential applications, including converting it to plastics, chemicals, fuels, as well as using carbon dioxide to replace high-emissions raw materials.

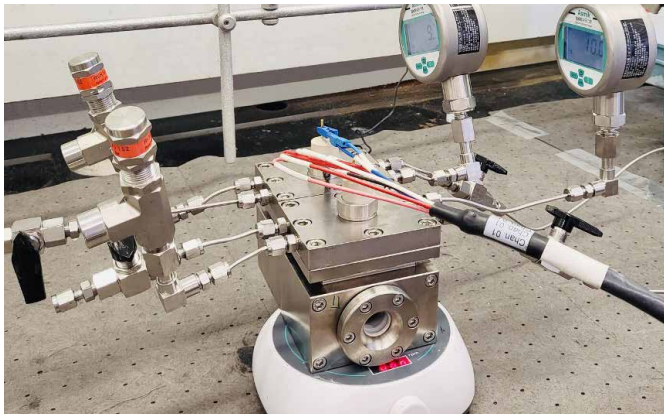
MAJOR FY24 ACCOMPLISHMENTS INCLUDE:

- A research team led by Dr. Hazari succeeded in creating a highly active and selective photo-electrocatalyst for converting CO_2 to formate by attaching a molecular manganese (Mn) catalyst with a silatrane functional group to thermally oxidized porous silicon (Si). The team is preparing a manuscript related to these findings and is in the process of filing for a provisional patent for the system.

- YCNCC scientists led by Dr. Wang continued to advance the chemistry, materials, and reactor engineering to improve the CO_2 to methanol conversion process, overcoming a key limiting step of CO_2-to-methanol conversion, and has developed a viable system for practical application.

- The Wang team filed a patent application for their technology, which is being licensed by a newly-formed company (Oxylus Energy) to further develop and commercialize the technology. Oxylus Energy has raised $4.5 million (led by Toyota) for its efforts.

- A research team led by Dr. Wang and Dr. Winter have established two new reactor systems to demonstrate the first example of plasma-electrocatalytic CO_2 conversion, including generation of novel and high-value products. A provisional patent is being prepared for this work.Through their research, the team is continuing to gain a deeper understanding of these processes with the goal of better controlling the generation of high-value products. A reactor developed with YCNCC funding led to a Beckman Young Investigator Award to Dr. Winter that provides research funds to develop a novel method of producing ammonia for fertilizer, addressing the long-standing challenge of reducing carbon emissions while increasing global access to fertilizer.



High-pressure electrochemical reactor

Photo provided by Wang Research Lab

NEW HIRES

FACULTY AND STAFF

Dr. David Kwabi
Department of Chemical & Environmental Engineering

ABOUT

Professor David Kwabi will join the YCNCC in January 2025 as its fifth new faculty hire, and will be a member of the Department of Chemical & Environmental Engineering faculty in the School of Engineering and Applied Sciences. Dr. Kwabi has a BSc from Princeton University, a PhD from MIT, was a postdoctoral researcher at Harvard University, and has been on the faculty of the University of Michigan since 2019. His research encompasses the study and use of electrochemistry and photochemistry in energy storage and conversion, desalination, and atmospheric and marine carbon capture and utilization.

Toby Bryce
Managing Director for the Yale Center for Natural Carbon

ABOUT

Toby Bryce joined Yale in 2024 as YNCC's Managing Director to lead administration, communications, development, and external affairs. Prior to Yale, he was engaged broadly across the natural carbon capture field as an advisor to companies and organizations on policy, market development, and the responsible commercialization and deployment of high-integrity CO2 removal. Bryce holds a BA in Environmental Policy from the University of Virginia, and served as a Peace Corps Volunteer in Costa Rica.

Postdoctoral Fellows

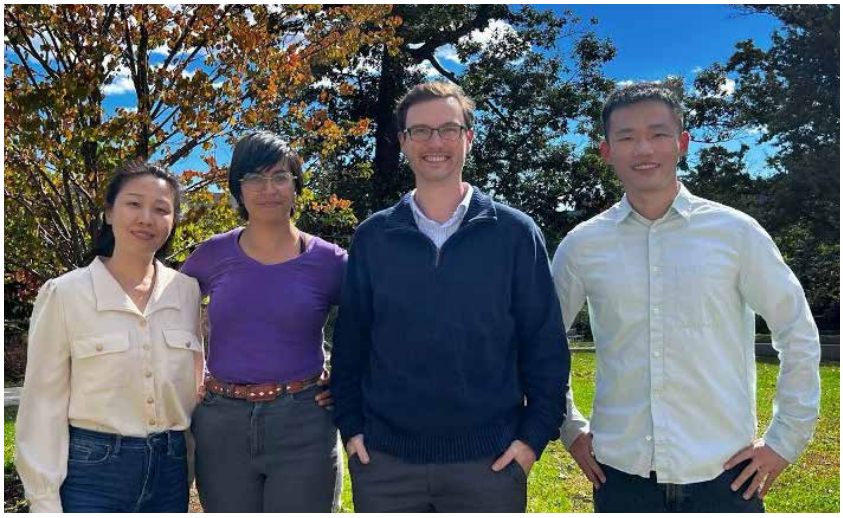
Attracting and supporting early career researchers that bring novel ideas and perspectives to Yale and the Center is a key mechanism for enabling innovative and cutting-edge science for solving the climate crisis. To this end, YCNCC funds two postdoctoral fellowships per year, with two new Fellows arriving in Fall 2024 to join the two current YCNCC Fellows. Their projects will expand the research portfolio of the Center and address topics that have the potential to significantly contribute to informed climate solutions (please see Appendix C for project details). The current YCNCC Postdoctoral Fellows are:

Dr. Mariela Garcia Arredondo (August 2024 - July 2026)
Faculty Advisor: Dr. Eric Slessarev, Assistant Professor of Ecology and Evolutionary Biology
Department/School: Ecology and Evolutionary Biology Department
Focus area: Ecosystem Capture
Planned research project: Linking Soil Carbon and the Calcium Cycle in Grassland Ecosystems

Dr. Shangshi Liu (October 2024 - September 2026)
Faculty Advisor: Dr. Mark Bradford, Professor of Soils and Ecosystem Ecology
Department/School: School of the Environment
Focus area: Ecosystem Capture
Planned research project: Regenerative Agriculture for Rebuilding Soil Organic Carbon Stock

Dr. Spencer Moller (August 2023 - August 2025)
Faculty Advisor: Dr. Ruth Blake, Professor of Earth & Planetary Sciences
Department/School: Earth and Planetary Sciences Department
Focus area: Enhanced Rock Weathering
Planned research project: Phosphate Oxygen Isotopes: A Proxy to Link Carbon Capture and Biogeochemical Cycling of Phosphorus in Agricultural Soils

Dr. Fan Yang, Industry Fellow (January 2024 - December 2025)
Faculty Advisor: Dr. Yuan Yao, Associate Professor of Industrial Ecology and Sustainable Systems
Department/School: School of the Environment
Focus area: Industrial Decarbonization
Planned research project: Decarbonizing the Aviation Sector by Carbon Capture and Utilization



YCNCC Postdoctoral Fellows Dr. Fan Yang, Dr. Maria Garcia Arredondo, Dr. Spencer Moller, and Dr. Shangshi Liu

Photo provided by YCNCC

YCNCC-ENDOWED FACULTY UPDATES

Over the course of FY24, the YCNCC-endowed faculty who joined Yale in 2023 have settled into their new positions, established their labs, and are already advancing a number of important and impactful research projects in their respective areas of expertise. Please see Appendix B for full details of YCNCC-endowed faculty activities in FY24.

FY24 HIGHLIGHTS INCLUDE:

- Yale School of the Environment (YSE) Associate Professor Dr. Paulo Brando was awarded a $2.5 million NSF grant to study the cascading impacts of Amazon forest fragmentation.
- Earth & Planetary Sciences (EPS) Associate Professor Dr. Matthew Eisaman published several significant papers on electrochemical ocean alkalinity enhancement for mCDR and is part of YCNCC's DOE Earthshot research team that was awarded $5 million in new grant funding.
- YSE Assistant Professor Dr. Sparkle Malone led a YCNCC-funded workshop on "Observation Infrastructure for Natural Methane Emissions," and presented her research on terrestrial methane dynamics in several major forums including the Ecological Society of America, NASA's Blue Flux Team Meeting, and at Harvard University.
- Ecology & Evolutionary Biology (EEB) Assistant Professor Dr. Eric Slessarev was awarded over $1.1 million in new grant funding from DOE and Lawrence Livermore National Laboratory to study the role of soil in terrestrial ecosystems and soil-based climate mitigation strategies.

YCNCC-endowed faculty Dr. Paulo Brando, Dr. Eric Slessarev, Dr. Sparkle Malone, and Dr. Matthew Eisaman

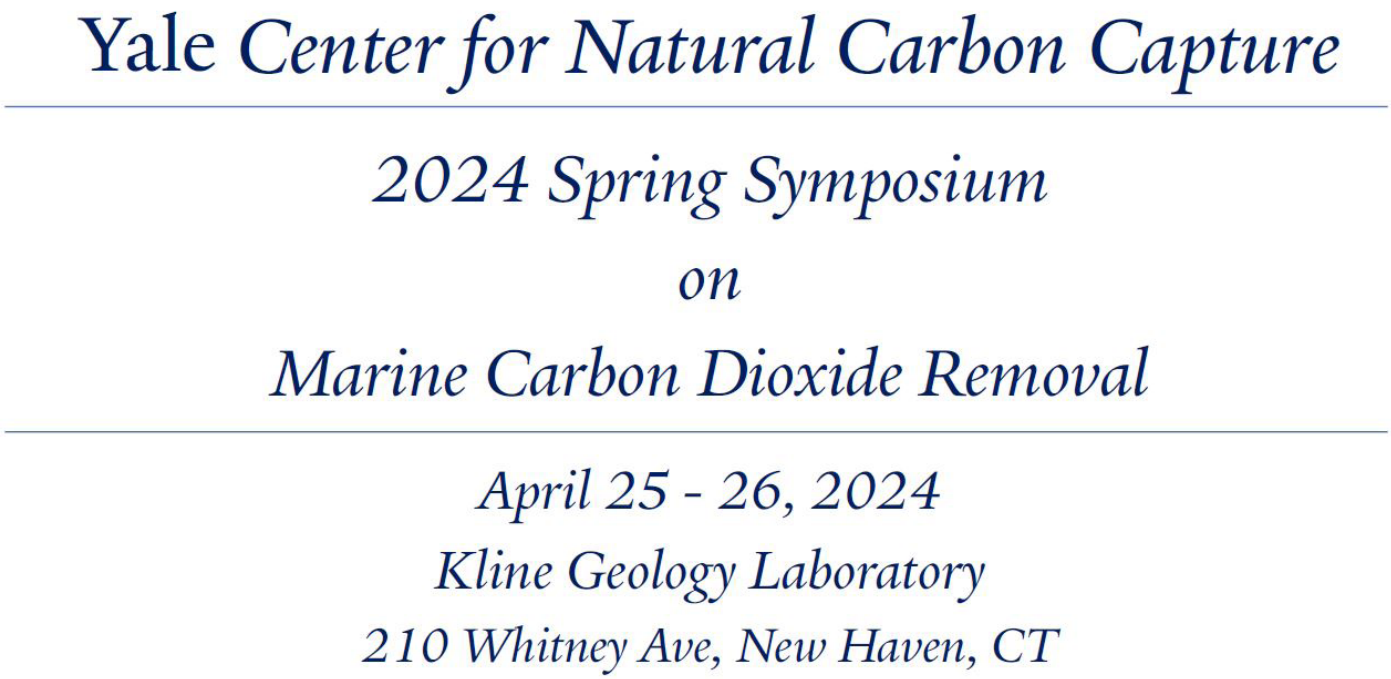
Photo provided by YCNCC

YCNCC 2024

SPRING SYMPOSIUM

YCNCC's second annual Spring Symposium focused on the potential for mCDR to play an integral role in mitigating the climate crisis. The two-day meeting in April 2024 brought together over 300 thought leaders from academia, government, NGOs, and the private sector for a series of talks, panels, and networking opportunities focused on the current state of mCDR and how to advance the field to make a meaningful impact on the climate crisis.

Attendees heard from the world's preeminent scientists and researchers, high-level government representatives from DOE, NOAA, and a number of private companies working to deploy, support, and advance mCDR solutions, including: Google, Microsoft, [C]Worthy, Isometric, Banyu Carbon, Calcarea, Hourglass Climate, Aquatic Labs, Planetary Technologies, Captura, Equatic, Ebb Carbon, Carbon180, Oceans Visions. Highlights included a keynote talk by Dr. Sarah Kapnick, Chief Scientist for NOAA, and panels addressing *Monitoring, Reporting, and Verification – Challenges and Opportunities*; *The State of mCDR Carbon Removal Purchases and Investment*; and *Responsible deployment of mCDR*. See Appendix G for an outline of the full Symposium program.



YCNCC
WORKSHOP PROGRAM

The workshop program at YCNCC is a primary means by which the Center facilitates connections and collaborations between Yale researchers and their counterparts worldwide, spanning various institutions, sectors, and fields. The YCNCC workshop program leverages Yale's reputation and resources to convene top experts from around the world. Workshop proposals must clearly state the expected outcomes, how the workshop will advance the field, and its relevance to the Center's mission.

Six YCNCC-funded workshops took place in the past year, focusing on the following topics (see Appendix F for full details):

- Observation Infrastructure for Natural Methane Emissions (September 2023)
- Carbon and Coffee Workshop: The Role of Tropical Crops in Natural Carbon Capture (September 2023)
- The Pressing Need for Incorporating Belowground Processes in Tropical Forest Restoration (November 2023)
- Tropical Soil Fertility and Forest Dynamics Workshop (February 2024)
- Tropical Forest Fires: An Integrated View to Avoid the Tipping Point (March 2024)
- Toward an R&D Roadmap to Quantify and Reduce Uncertainty in MRV for Abiotic mCDR (April 2024)

Attendees of the September 2023 YCNCC methane workshop

Photo provided by Dr. Sparkle Malone

WORKSHOP PROGRAM

Participants

182 Universities

47 Non Profit Organizations

20 Government

14 Industry

OUTREACH AND ENGAGEMENT

Over the course of FY24, YCNCC scientists engaged with a wide range of audiences. (See Appendix G for a list of all activities.) This included academic engagement, both internally through YCNCC's Fall 2023 Research Showcase that brought together researchers from across Yale's campus, as well as externally, by presenting research results at national and international conferences and in invited talks at other institutions. YCNCC researchers also engaged with students and the general public through a range of outreach programs in which we shared information about climate change science and solutions. In terms of corporate engagement, YCNCC led three corporate webinars as well as the Fall 2023 Corporate Roundtable meeting that collectively drew over 225 attendees.

In addition, YCNCC collaborates with and provides funds to Yale's Environmental Leadership & Training Initiative (ELTI) to create educational resources and offer training focused on natural carbon capture and carbon markets. These opportunities are aimed at practitioners, decision-makers, and corporate audiences. Since 2006, ELTI has provided a diverse range of field and online training programs to over 5,000 individuals involved in conservation and restoration efforts in tropical forest landscapes. ELTI works closely with Yale faculty and a global network of partners and experts to design and implement its field-based and online activities.

ELTI FY24 HIGHLIGHTS INCLUDED:

- 177 people trained during 6 field courses and 1 blended course on themes related to natural carbon capture in Brazil, Colombia, Panama, and Indonesia
- 360 people from 50+ countries trained during 5 online short courses and Cohort 5 (June 2023-May 2024) of the yearlong certificate on themes related to natural carbon capture
- 290 people attended at least one of four webinars focused on carbon and agroforestry
- 16 new lectures developed on climate change, carbon markets, and other themes directly related to natural carbon capture for the yearlong online certificate program
- 40+ ELTI alumni supported in Brazil, Panama, Colombia, and Indonesia via the Leadership Program to implement on-farm restoration and sustainable agricultural projects and work on publications and research related to natural carbon capture
- $654,413 in funding secured to support program activities, including the launch of a new field program in Rwanda on forest and landscape restoration and workshops to advance the development of two online courses on carbon markets for the buyers of carbon credits and blue carbon

An Indonesian community partnering with ELTI to construct a mangrove honey production

Photo provided by ELTI

DIVERSITY, EQUITY, AND INCLUSION

PLAN AND IMPLEMENTATION

The Center's Diversity, Equity, and Inclusion strategy is built on two pillars: 1) creating an inclusive and equitable work environment, and 2) addressing the social dimension of studying and implementing climate solutions.

THE CENTER'S DIVERSITY, EQUITY, AND INCLUSION STRATEGY

Creating an inclusive and equitable work environment.

Addressing the social dimension of studying and implementing climate solutions.

Specific actions the Center implemented over the last year to advance the strategic diversity, equity, and inclusion plan include:

- Establishing clear, transparent, and detailed documentation for activities and programs at the Center
- Establishing committees and rubrics for various decision-making processes such as postdoctoral fellowship awards and research awards
- Ensuring accessibility of Center events and activities by providing special accommodation when needed, such as various ways to participate (remote and in person), flexibility whenever possible to enable caregivers to participate, actively inquiring about any other specific needs such as dietary restrictions, transportation needs and more.
- Actively diversifying how the Center advertises opportunities, such as fellowship positions, to reach underrepresented demographics
- Selecting speakers and panelists to represent diverse perspectives, based on geographic or ethnic origin, sector or field of expertise, or career stage
- Providing funding to the Environmental Training and Leadership Initiative, which directly works with practitioners implementing nature-based climate solutions on the ground in low and middle income countries
- Encouraging best diversity, equity, and inclusion practices from all grants, fellowship, or workshop applications

LEADERSHIP AND PERSONNEL

Faculty Directors

Liza Comita
Professor of Tropical Forest Ecology, Yale School of the Environment

Dave Bercovici
Professor of Earth and Planetary Sciences, Department for Earth and Planetary Sciences

The faculty directors set the research agenda for the Center, develop the long term strategic vision for the Center and oversee the implementation of Center programs and activities

University Assigned Staff

Outreach and Corporate Engagement Manager
Lauren Steele

The Outreach and Corporate Engagement Manager manages corporate partnerships and engagement activities and serves as the main point of contact for the Center's corporate partners.

Operations Manager
Steven Choi

The operations manager provides financial and administrative support to the Center and ensures compliance with university and government guidelines.

Director of Finance and Administration
Harley Pretty

The director of finance and administration oversees the Center finances, budgeting and spending

Core Center Staff

Managing Director
Toby Bryce

The managing director sets up and implements Center programs and activities, establishes and maintains the administrative structure and manages the Center's Day-to-day activities

Senior Administrative Assistant
Kat Gaynor

The senior administrative assistant coordinates schedules and meetings and organizes event logistics.

Student Assistants
Raysieo Duakin & Aishwarya Kurade

Student assistants support coordinating and organizing the Spring Symposium.

Steering Committee

The steering committee provides guidance on the Center strategy and helps stewarding the Center resources

Mark Ashton
Senior Associate Dean of The Forest School; Professor of Silviculture and Forest Ecology

Jeffrey Brock
Dean, Yale School of Engineering & Applied Science, Professor of Mathematics

Gary Brudvig
Professor of Molecular Biophysics and Biochemistry

Indy Burke
Dean, Yale School of the Environment, Professor of Ecosystem Ecology

Michael Crair
Vice Provost for Research, Professor of Neuroscience, and Professor of Ophthalmology and Visual Science

Robert Dubrow
Professor of Epidemiology

Larry Gladney
Dean of Science and Dean of Diversity and Faculty Development in the Faculty of Arts and Sciences; Professor of Physics

Maureen Long
Professor and Chair of Earth & Planetary Sciences

William Nordhaus
Professor of Economics and Professor of Forestry and Environmental Studies

Jordan Peccia
Professor and Chair of Chemical & Environmental Engineering

Gerald Torres
Professor of Environmental Justice

LEADERSHIP AND PERSONNEL

Scientific Leadership Team

The scientific leadership team advise the faculty directors on strategic decisions, head major research themes and provide direct connections to departments and schools across campus

Mark Bradford
Professor, Soils and Ecosystem Ecology, Yale School of the Environment

Paulo Brando
Associate Professor, Ecosystem Carbon Capture, Yale School of the Environment

Matt Eisaman
Associate Professor, Department for Earth and Planetary Sciences

Nilay Hazari
Professor and Chair, Department of Chemistry

Sara Kuebbing
Lecturer; Research Scientist; Research Director, Yale Applied Science Synthesis Program

Sparkle Malone
Assistant Professor, Ecosystem Carbon Capture, Yale School of the Environment

Noah Planavsky
Professor, Earth & Planetary Sciences, Department for Earth and Planetary Sciences

Pete Raymond
Professor, Forestry and Environmental Studies and of Geology and Geophysics, Department for Earth and Planetary Sciences

James Saiers
Professor, Hydrology, Yale School of the Environment

Eric Slessarev
Assistant Professor, Ecology and Evolutionary Biology, Department for Ecology and Evolutionary Biology

Mary-Louise Timmermans
Professor, Earth and Planetary Sciences, Department for Earth and Planetary Sciences

Julie Zimmerman
Vice Provost for Planetary Solutions, Professor of Green Engineering, Assistant Director for Research at Center for Green Chemistry and Green Engineering, Yale School of the Environment

CONCLUSION

2024 was a year of rapidly increasing momentum for YCNCC. YCNCC researchers continue to advance scientific, academic, and practical considerations surrounding carbon capture and storage. Key breakthroughs and cutting-edge research developed as part of the Center's work are not only uncovering new pathways for carbon removal, they are also helping to better define the impact of existing methods, and make those technologies and approaches more effective going forward.

Additionally, the Center's focus on cross-functional engagement with key stakeholders, spanning academia, industry, and government, is bringing together leading minds from multiple sectors and supporting high-level decision-making across the globe. New additions to YCNCC's faculty and management are helping to expand the Center's impact into the future.

The Center's work is laying the foundation for natural climate solutions and policies that are grounded in science, responsibility, and effectiveness. We remain excited about supporting our researchers' passion and unique combination of skills and expertise as they make significant contributions to the future of carbon removal.

APPENDIX A

RESEARCH PROJECTS

DETAILED UPDATES

ECOSYSTEM CAPTURE: TERRESTRIAL
Yale Applied Science Synthesis Program (YASSP)

PIs:

- Mark Bradford, Professor of Soils and Ecosystem Ecology
- Sara Kuebbing, Lecturer; Research Scientist; Research Director, Yale Applied Science Synthesis Program

RESEARCHERS AT YALE:

- Wyatt Klipa, Postgraduate Associate
- Weier Liu, Postdoctoral Researcher
- Lisa Eash, Postdoctoral Researcher
- Laura Toro, Postdoctoral Researcher
- Cole Gross, Postdoctoral Researcher
- Will Gardner, Graduate Student Researcher (MEM, MBA)
- Anna Stemberger, Graduate Student Researcher (MEM)
- Vincent Haller, Graduate Student Researcher (MESc)
- Jimena Terrazas Lozano, Graduate Student Researcher (MESc)

SCIENTIFIC PUBLICATIONS:

Published:

- Tan SX and SE Kuebbing. 2023. A synthesis of the effect of regenerative agriculture on soil carbon sequestration in Southeast Asian croplands. Agriculture, Ecosystems & Environment 349:108450. https://doi.org/10.1016/j.agee.2023.108450
- Wood SA, KTTU Hayhoe, MA Bradford, SE Kuebbing, PW Ellis, E Fuller, D Bossio. 2023. Mitigating near-term climate change. Environmental Research Letters 18:101002. https://doi.org/10.1088/1748-9326/acfdbd
- Bradford MA, L Eash, A Polussa, FV Jevon, SE Kuebbing, A Hammac, S Rosenzweig, EE Oldfield. 2023. Is it feasible to quantify the effect of agricultural practices on soil carbon stocks through sampling? Geoderma 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719
- Raffeld AM, MA Bradford, RD Jackson, D Rath, GR Sanford, N Tautges, EE Oldfield. 2024. The importance of accounting method and sampling depth to estimate changes in soil carbon stocks. Carbon Balance and Management 19:2. https://doi.org/10.1186/s13021-024000249-1

PROJECT OVERVIEW:

The Yale Applied Science Synthesis Program (YASSP) connects academic researchers, policymakers, and land management professionals to answer questions about how land management decisions affect the services provided by forests, croplands, wetlands, rangelands, and grasslands. With widespread interest in 'climate-smart' forestry and agriculture for climate mitigation and adaptation purposes, YASSP is focusing its work in forested and agroecosystems in tropical and temperate systems.

APPENDIX A
RESEARCH PROJECTS

The project aims to:

1) Synthesize and model carbon expected gains in response to ecosystem management changes
2) Review current methods and approaches for measuring carbon gains in response to ecosystem management
3) Convene and engage with land managers and policymakers who are pursuing carbon-based ecosystem management projects to bring the best available science to land management activities
YASSP works with for-profit and not-for-profit partners seeking to make decisions about sustainable land management practices and produces open and transparent public-good research, with the goal of promoting the widespread application and development of these findings. YASSP works to maximize ecosystem benefits provided by land resources, such as carbon storage, sustainable food production, and biodiversity.

RECENT ACCOMPLISHMENTS:

- YASSP researchers co-authored the U.S. DOE 'Roads to Removal' report, which lays out pathways for the US to remove at least 1 billion tonnes of CO2 per year from the atmosphere by 2050.
- A major limitation in scaling improved management practices for increasing carbon storage lies in the soil research community's lack of agreement on measuring and confirming soil carbon gains. Recent findings by YASSP researchers reveal a scarcity of empirical evidence supporting claims of reliably measuring soil carbon increases. While some scientists argue that it is infeasible to empirically measure soil carbon changes, initial work by YASSP researchers counters this argument, demonstrating that thoughtful experimental designs could reliably estimate soil carbon gains and provide guidelines for conducting rigorous soil sampling campaigns.
- YASSP researchers are also working to improve MRV protocols for carbon sequestration in soil – which is hindered by the limited availability of data – by providing a synthetic dataset of U.S. croplands available for public use.
- YASSP researchers are also highlighting how structural differences in MRV protocols impact the number of soil carbon credits attributed to specific projects, further emphasizing the need for continued research in additionality and uncertainty assessments to enhance confidence in MRV protocols.
- While there's widespread acknowledgment of forests' potential for climate mitigation and carbon capture, there's also widespread disagreement on the best forest management options and effective carbon tracking programs. YASSP research demonstrates how tailoring forest management to regional socioeconomic and environmental conditions and incorporating disturbance regimes can address this discord, leading to net forest carbon gains with many additional biodiversity, economic, and human health benefits.
- YASSP researchers have participated in a number of national summits, with the goal of reconciling competing narratives about forest management.
- The team is also advocating for more rigorous carbon crediting protocols in voluntary and compliance markets through participation in expert working groups, as well as hosting technical workshops that bring together academic and applied researchers.

APPENDIX A
RESEARCH PROJECTS

Carbon Storage and Capture in the Sinharaja Land Use Mosaic (Sri Lanka)

PIs:

- Luke Sanford, Assistant Professor of Environmental Policy and Governance
- Mark Ashton, Senior Associate Dean of The Forest School; Morris K. Jesup Professor of Silviculture and Forest Ecology; Director of Yale Forests
- Simon Queenborough, Senior Lecturer and Research Scientist; Musser Director, Tropical Resources Institute

RESEARCHERS AT YALE:

- David Woodbury, Doctoral Student

COLLABORATORS AT OTHER INSTITUTIONS:

- Sisira Ediriweera, Professor, Uva Wellessa University, Sri Lanka

PROJECT OVERVIEW:

This project focuses on studying tropical forests in South and Southeast Asia, which have a high carbon storage capacity. The research investigates how forest destruction for agricultural purposes has left fragmented forest ecosystems in the region, creating unique landscapes that differ from those in tropical Africa and Latin America. The study aims to determine how carbon storage in these forest fragments is influenced by the history of land use in neighboring areas and estimate the potential for carbon sequestration through forest restoration.

The Sinharaja region in Sri Lanka provides an ideal setting for this research as it offers seventy years of government land records and aerial images documenting forest clearance, conversion, and forest fragment history. Such detailed documentation is rare in Asia and the tropics, making this an exceptional opportunity for further research.

By documenting carbon storage and sequestration in forest fragments and analyzing their relation to historical and socio-economic geography, this study will be the first in Asia to shed light on how policy changes in the surrounding landscape impact carbon storage and sequestration within forest fragments. The results have the potential to inform targeted conservation efforts that maximize carbon sequestration potential.

RECENT PROGRESS:

- The team has measured biomass in over 200 plots across various land cover types and created seamless mosaics from aerial imagery from 1956 to 2022.

- By gathering remote sensing imagery from 2000 to present and building machine learning models to accurately estimate biomass from this aerial imagery, the team will be able to analyze biomass changes over time and gain greater insights into the impact of these regions.

APPENDIX A
RESEARCH PROJECTS

A Case Study of Industrial Reforestation in Mata Atlantica, Brazil

PIs:

- Mark Ashton, Senior Associate Dean of The Forest School; Morris K. Jesup Professor of Silviculture and Forest Ecology; Director of Yale Forests
- Luke Sanford, Assistant Professor of Environmental Policy and Governance
- Yuan Yao, Assistant Professor of Industrial Ecology and Sustainable Systems, Yale School of the Environment

RESEARCHERS AT YALE:

- Owen Cortner, Postdoctoral Researcher
- Bingquan Zhang, Postdoctoral Researcher
- Fan Yang, Postdoctoral Researcher
- Thomas Harris, Doctoral Student
- Manny Flores, Doctoral Student
- Yeim We, Master Student
- Odatha Kotagama, Master Student

COLLABORATORS AT OTHER INSTITUTIONS:

- Daniel Piotto, Federal University of Southern Bahia

PROJECT OVERVIEW:

Because of government mandates that require landowners to conserve at least 20 percent of their land as native forests, Brazil's Mata Atlantica region provides a compelling case study in which to examine the impacts of reforestation efforts on agricultural and pasture lands. This natural forest regrowth on industrial plantations in the region has the potential to sequester carbon in the landscape and wood products and could provide a scalable model for reforestation efforts that sequesters carbon while providing biological and economic benefits.

The project aims to measure the land cover effect of government mandated reforestation efforts in the Mata Atlantica region as compared to other land uses; determine the reforestation effect on biomass and carbon sequestration in production and protection forest as compared to de-facto land uses; develop and implement a pixel-based counterfactual estimation strategy to assess the overall impact of commercial reforestation efforts; evaluate the land tenure arrangements for the reforestation enterprise and effects on human population demographics and landowner income; and generate a life cycle assessment (LCA) for carbon changes in plantation and natural forests, which estimates the contribution potential for these forests in capturing atmospheric CO_2.

RECENT ACCOMPLISHMENTS:

- The team has conducted fieldwork to verify and validate satellite-based assessments of the region generated in 2022. The data have been analyzed, written up as a draft manuscript, and presented at several conferences.
- The team has estimated above-ground carbon stocks using forest/pasture coverage data, extensive in-situ forest inventory

APPENDIX A
RESEARCH PROJECTS

plots, and allometric equations. Estimates for below-ground carbon stocks were generated by collecting, processing, and analyzing soil samples for major nutrients and carbon. These results have been presented at two research conferences.
- The team conducted remote sensing analysis to assess how surrounding land uses influence forest growth. Initial findings point to an impact on overall plant height but not necessarily plant health. These results are being verified through sensitivity analysis and on-the-ground forest inventory analysis.
- The team is developing a counterfactual model to estimate what forest cover and carbon stock levels would have been without reforestation efforts.
- The team conducted interviews with key stakeholders in the region and is analyzing the potential impacts on population demographics and landowner incomes of alternative land use scenarios.
- Finally, the team has analyzed and estimated the total carbon impact of various land-use scenarios, finding that land used for CLT-biochar production achieves a net removal of -33.8 Gt CO_2e, while secondary natural regrowth accounts for -30.7 Gt CO_2e over 100 years. In contrast, land used for pulp and paper production generates net GHG emissions of 15.5 Gt CO_2e.

Understanding Temperate Liana Ecology and Impacts Using Species Distribution Models, Uav Remote Sensing and In Situ Field Experiments

PIs:

- Jacob Peters, Doctoral Student
- Mark Ashton, Senior Associate Dean of The Forest School; Morris K. Jesup Professor of Silviculture and Forest Ecology; Director of Yale Forests
- Xuhui Lee, Sara Shallenberger Brown Professor of Meteorology

RESEARCHERS AT YALE:

- Sangam Paudel, Postgraduate Assistant
- Yeim We, Postgraduate Assistant
- Chomri Khayi, Postgraduate Assistant

COLLABORATORS AT OTHER INSTITUTIONS:

- Bronson Griscom, Conservation International
- Grant Connette, Smithsonian Conservation Biology Institute
- Riley Johnson, Washington College, Maryland

SCIENTIFIC PUBLICATIONS:

Published:

- Peters JDJ, Portmann JM and Griscom BW (2023) Lianas (Vitis spp.) reduce growth and carbon sequestration of light-demanding tree species in a temperate forest. Restor Ecol. 31(5), 1-10. doi.org/10.1111/rec.13886

APPENDIX A
RESEARCH PROJECTS

PROJECT OVERVIEW:

This project focuses on using drones, remote sensing technologies, and field methods to study how woody vines affect temperate forest growth and carbon storage rates. The project aims to develop habitat suitability models that will include current and future ranges for several species of woody vines and predict their distribution across North America; use high resolution multispectral imagery and lidar to obtain high-resolution images of the forest canopy to pursue the goal of differentiating dead trees, canopy gaps, healthy trees, vine-laden trees, and other surface features; conduct field experiments to test the benefits and drawbacks of cutting vines as a forest management practice for increased growth and carbon sequestration; and develop a first-of-its-kind tree growth map to determine the carbon benefits of the removal of various woody vine species across North America.

RECENT ACCOMPLISHMENTS:

- The team has created preliminary maps of current and future habitat ranges for seven woody vines species in North America. Preliminary observations indicate that non-native woody vines species appear limited to urban-forest boundaries, indicating that management strategies could be most effective along these boundaries.
- Using UAV multispectral camera and lidar, the team has conducted preliminary mapping of sites in West Virginia, Maryland and Connecticut, and has started using this imagery to differentiate dead trees, canopy gaps, healthy trees, vine-laden trees, and other surface features.
- The team has secured a $25,000 grant from the Yale Forest School Childs Fund to establish a test and calibration site at Yale Myers Forest. This site will be used to test and observe the impacts of climate-related phenomena, such as droughts, flooding, storms, insect outbreaks, as well as woody vine infestation.

Integrating Megafauna with Ecosystem Carbon Cycling: A Multiscale Analysis of Moose Management to Enhance Boreal Forest Carbon

PIs:

- Oswald Schmitz, Oastler Professor of Population and Community Ecology

RESEARCHERS AT YALE:

- Elizabeth Forbes, Postdoctoral Researcher

COLLABORATORS AT OTHER INSTITUTIONS:

- Dr. Shawn Leroux, Professor, Department of Biology, Memorial University

PROJECT OVERVIEW:
While plants and microbes are widely recognized for their role in the carbon dynamics of various ecosystems, the impact of animals, from small to large, in influencing carbon uptake and storage within these ecosystems is less well understood.

APPENDIX A
RESEARCH PROJECTS

The project specifically focuses on moose, a large-bodied vertebrate, and aims to quantify how moose population densities and resulting forest disturbance impact carbon storage and soil carbon dioxide emissions in a boreal forest landscape. Understanding the interplay between moose populations, forest disturbances, and carbon dynamics will provide valuable insights for conservation strategies in the boreal and other biomes, helping optimize moose population management for carbon sequestration and other societal values like hunting and tourism. The findings will also inform Parks Canada's management decisions in relation to carbon optimization and other social values.

RECENT ACCOMPLISHMENTS:

- The team conducted soil sampling at 35 sites across the Terra Nova and Gros Morne National Parks in Newfoundland, Canada, with a focus on collecting higher resolution samples to improve statistical models of soil carbon dynamics.
- The team also conducted a proof of concept of its "Fluxbot" tool – which allows for continuous monitoring of soil emissions in a given area. In a Massachusetts field test, the team successfully used an updated Fluxbot design to collect hourly data on soil CO_2 respiration.
- The team is in the process of deploying a Fluxbot array in Newfoundland, with the aim of capturing ecologically-meaningful patterns in soil carbon changes across varying moose density environments.
- In Newfoundland, the team found that soil carbon rates vary with moose population density but this variability differs across different forest scenarios, such as canopy gaps and mature forest patches. The findings did not point to a clear signal of higher flux rates in any particular forest treatment, which is likely due to the competing interactions between drivers of soil carbon flux.
- During the Fluxbot proof of concept deployment, the team found that data collected closely matched that of data collected by long-standing devices deployed in the area, confirming the performance of the Fluxbot array. In addition, this deployment demonstrated the utility of a distributed array of Fluxbots in detecting small-scale differences in soil carbon flux rates.

The Natural Carbon Consequence of Cross Laminated Timber

PIs:

- Yuan Yao, Assistant Professor of Industrial Ecology and Sustainable Systems
- Robert Mendelsohn, Edwin Weyerhaeuser Davis Professor of Forest Policy; Professor of Economics; and Professor, School of Management

RESEARCHERS AT YALE:

- Hannah Wang, Graduate Student
- Kai Lan, Postdoctoral Researcher

COLLABORATORS AT OTHER INSTITUTIONS:

- Alice Favero, Senior Environmental Economist, RTI International

APPENDIX A
RESEARCH PROJECTS

PROJECT OVERVIEW:

This project focuses on cross-laminated timber (CLT), an emerging wood product used in mid- and high-rise buildings, which can help mitigate climate change by storing carbon directly and replacing other more carbon-intensive construction materials. While CLT represents a promising product, its large-scale adoption could have unintended impacts on global forests and relevant carbon pools.

To address these concerns, the project aims to provide a comprehensive understanding of the net carbon consequences of CLT throughout its lifecycle and its impact on forest carbon sequestration at a large scale. The project combines a consequential life cycle assessment (LCA) and a global timber model to quantify direct carbon emissions across CLT's lifecycle, including tree planting and harvesting, wood production, manufacturing, building use, demolition, and end-of-life. The analysis also considers the emissions avoided by substituting CLT for carbon-intensive construction materials. Additionally, the global timber model projects the carbon fluxes associated with changes in the timber market and forests, taking into account standing forest, slash, and soils.

This integrated analysis aims to determine the potential role of CLT in climate mitigation. The results will inform forest and carbon policy-making processes, improve the design and operations of forest-CLT-building systems, and support the development of scalable natural climate solutions. Ultimately, this project's outcomes will contribute to more sustainable practices in the construction industry and help combat climate change through the use of CLT and other innovative wood materials.

RECENT ACCOMPLISHMENTS:

- The team successfully integrated GTM, an ecological-economic model of the global timber market, into life cycle assessment models to determine the global carbon and land impacts of plausible future CLT growth scenarios.
- While previous studies have demonstrated that CLT reduces GHG emissions by substituting for steel and cement, the team's work is among the first to consider GHG emissions associated with indirect impacts of CLT – such as the manufacturing and disposal of the material.
- The team's results ultimately confirm the positive consequences of adopting CLT on increasing the forest carbon stock and decarbonizing the construction sector.
- The team found that wide scale adoption of CLT by 2100 would increase productive forest land by around 30.7–36.5 million hectares, resulting in an estimated global long-term carbon storage of 20.3–25.2 $GtCO_2e$, driving a total net reduction of life-cycle GHG emissions of 25.7–39.4 $GtCO_2e$. This reduction is primarily attributed to the increased carbon stock in forests and CLT panels, along with GHG reductions by traditional wood products and potential benefits by substituting traditional building materials and market electricity.
- The team has developed a paper outlining its findings, which is currently under review in Nature Communications, and has presented its findings at seminars and conferences.

APPENDIX A
RESEARCH PROJECTS

Molecular Tools for Resolving Microbial Methane Production and Oxidation in Natural Systems

PI:
- Jordan Peccia, Thomas E. Golden, Jr. Professor and Chair of Chemical & Environmental Engineering
- Peter Raymond, Senior Associate Dean of Research & Director of Doctoral Studies; Oastler Professor of Biogeochemistry
- Mark Bradford, Professor of Soils and Ecosystem Ecology

RESEARCHERS AT YALE:

- Wyatt Arnold, Graduate Student
- Cade Brown, Undergraduate Student
- Jon Gewirtzman, Graduate Student

COLLABORATORS AT OTHER INSTITUTIONS:

- Qespi Woods, Undergraduate Student, Universidad Nacional de San Antonio Abad del Cusco (Peru)

PROJECT OVERVIEW:

In recent years, scientists have discovered that tree stems are a significant source of methane release across various forest types. This process has the potential to negate or significantly diminish methane capture methane captured in nearby soils. While these methane fluxes are likely primarily microbial in origin, many open questions remain with regard to magnitude, drivers, and spatiotemporal patterning.

The aim of this project is to develop tools for quantifying the microbial methane production and uptake in natural environments and apply these tools to wetlands and living wood. The project's main objectives include determining how gene activity is related to the rates at which methane is produced and absorbed by microbes; and measuring the rates of microbial methane production and absorption in different parts of trees and comparing these rates across various tree species and types of tree tissue.

RECENT ACCOMPLISHMENTS:

- The team has successfully developed digital PCR approaches for key methanogen and methanotrophy genes in bacteria. These have been used to demonstrate that spatial heterogeneity in wetland methane production is strongly associated with methanogenesis activity.
- The team has developed a new approach for extracting microbial nucleic acids from the wood of living trees.
- The team has explored the microbial ecology in over 150 trees in Northeastern hardwood forests and determined that the ecology is a result of function and growth, rather than dispersion, indicating the importance of the microbial ecology to tree and forest health.
- Finally, the team has measured methane emissions and microbial ecology in over 150 hardwood species and have built associations between methane production, microbial activity, and tree species.

APPENDIX A
RESEARCH PROJECTS

SCIENTIFIC PUBLICATIONS:

Published:

- Arnold, W., Taylor, M.A., Bradford, M.A., Raymond, P.A., Peccia, J. (2023) "Microbial activity contributes to spatial heterogeneity of wetland methane fluxes" Microbiology Spectrum. 11(5) e02714-23.
- Arnold, W., Gewirtzman, J., Raymond, P.A., Bradford, M.A., Butler, C., Peccia, J. (2024) "A method for sampling the living wood microbiome. in press, Methods in Ecology and Evolution. https://doi.org/10.1111/2041-210X.14311
- Wyatt Arnold, Jonathan Gewirtzman, Peter A. Raymond, Marlyse Duguid, Craig Brodersen, Cade Brown, Naomi Norbraten, Qespi T'ika Vizcarra Wood, Mark A. Bradford, Jordan Peccia (2024)"A diverse and distinct microbiome inside living trees" (2024-05-11045) Nature.

The Whole-Ecosystem Carbon Sequestration Potential of Savanna Ecosystems and its Biodiversity Cost

PI:

- Carla Staver, Professor of Ecology and Evolutionary Biology; Associate Director of The Yale Institute for Biospheric Studies

RESEARCHERS AT YALE:

- Juliana Teixeira, Postdoctoral Researcher

COLLABORATORS AT OTHER INSTITUTIONS:

- Yong Zhou, Assistant Professor, Utah State University

PROJECT OVERVIEW:

The world's savanna regions, which are mixed woodland and grassland ecosystems, are increasingly being discussed as degraded forests and targeted for restoration – specifically reforestation initiatives that promise to bring about substantial carbon sequestration.

Despite this trend, direct or empirical observations of the actual carbon sequestration potential of savanna ecosystems do not exist. Further, recent research indicates that actual carbon sequestration associated with reforestation efforts of savanna ecosystems may be substantially lower than expected. This project aims to further an understanding of the carbon sequestration potential of savanna ecosystems and evaluate the biodiversity costs of carbon sequestration projects through field studies in Brazil.

RECENT ACCOMPLISHMENTS:

- The team traveled to Aguas de Santa Barbara, Brazil, to chart a sampling plan for the next two years.
- The team began sampling belowground carbon under different grazing and use histories.
- The team is conducting a literature review with regards to the entire ecosystem carbon distribution across various plantations.
- The team has completed an analysis of allometric relationships of savanna vs. forest trees in the sampling region.

APPENDIX A
RESEARCH PROJECTS – DETAILED UPDATES

ECOSYSTEM CAPTURE: BLUE CARBON
Developing a Blue Carbon Enhancement Plan for Sri Lanka

PI:

- Anitra Thorhaug, President & Chair of Board, Greater Caribbean Energy and Environment Foundation
- Graeme P. Berlyn, E. H. Harriman Professor of Forest Management and Physiology of Trees [1]

COLLABORATORS AT OTHER INSTITUTIONS:

- Edward Manning (Environment Canada, retired)
- Kevin Gallagher (EverWind Fuels, Yale BS 2020)

SCIENTIFIC PUBLICATIONS:

Published:

- Perwiki, A.,Thorhaug, A., Berlyn, GP, et al. 2024 Sri Lanka Seagrass Map. Botany 2024. Abstracts Pp 54. A-764

PROJECT OVERVIEW:

Sri Lanka offers an ideal case study to understand the carbon removal potential of blue carbon ecosystems. The island nation has 510,000 square kilometers of coastal resources, is well positioned oceanographically with waters rich in dissolved-carbonate compounds, and has publicly expressed the goal of becoming a model for enhancement of its blue carbon. Despite this, little is known about the extent of blue carbon resources in the country.

The goal of this project is to facilitate a better understanding of these resources and their carbon removal potential. To do this, researchers are working to map the total amount of seagrass and mangrove blue carbon resources in the country. Additionally, this project is bringing together a government committee on Seagrass Blue Carbon to develop a plan for protecting and enhancing blue carbon resources in Sri Lanka.

The potential climate impacts of protecting and enhancing Sri Lanka's blue carbon ecosystems is significant: recent estimates suggest that seagrass meadows and mangroves in Southeast Asia and the Caribbean alone have the capacity to store more carbon than all the world's tropical forests.

RECENT ACCOMPLISHMENTS:

- The team helped to form a national committee bringing together stakeholders around the country interested in restoring and enhancing seagrass blue carbon resources.
- The team is progressing in developing the first detailed map of Sri Lanka seagrass resources, identifying separate seagrass regions within the country and, for the first time, estimating the extent of seagrass along the eastern coast – a critical step for calculating the total extent of seagrass in Sri Lanka. These estimates will be compared to actual measurements planned for the fall of 2024.
- Finally, the team has initiated a new tool for resource managers that will help them to identify locations where seagrass restoration will be most successful and beneficial.

[1] Graeme P. Berlyn, a world-renowned expert on the anatomy and physiology of plants and trees who taught at the Yale School of the Environment (YSE) for more than 60 years, died February 16 in Hamden, Connecticut. He was 90.

APPENDIX A
RESEARCH PROJECTS

Thermal Variation and Acclimation Impact Biomass Accumulation of Photosynthetic Algae

PI:

- David Vasseur, Professor of Ecology and Evolutionary Biology

RESEARCHERS AT YALE:

- Carling Bieg, Postdoctoral Researcher, Yale Department for Ecology and Evolutionary Biology

SCIENTIFIC PUBLICATIONS:

Published:
- Bieg C & Vasseur D. 2024. Interactions between temperature and nutrients determine the population dynamics of primary producers. Ecology Letters 27(1): e14363. DOI:10.1111/ele.14363

PROJECT OVERVIEW:

Algae are responsible for nearly half of the global carbon fixation and are fundamental to bottom-up regulation of all aquatic systems. However, carbon that is stored into algal biomass is readily available as a food source for herbivores. It therefore quickly moves through the aquatic food chain and is returned to the atmosphere via respiration. Because of this, only a small amount of CO_2 captured by algae is ultimately permanently sequestered in deep lake or ocean sediments. Further complicating the CO_2 sequestration potential of algae is changing global temperatures resulting from global warming. As temperatures rise, the flow of nutrients and energy in aquatic food chains will be altered in varying ways, creating a substantial impact on the fate of fixed carbon in aquatic systems.

The aim of this project is to improve the understanding of how these temperature variations will impact the potential for algae to grow and accrue biomass, which is fundamental to understanding the carbon sequestration impact of algae.

RECENT ACCOMPLISHMENTS:

- The team published a paper that shows how changes in nutrients and temperature can influence algal production and biomass – a theory not considered in current models. In this paper, the researchers demonstrated that the most efficient way for a population of photosynthetic algae to reach high biomass is to begin growing at warm temperatures and, once abundant, transition to cooler temperatures.
- The researchers are now working on an applied version of this theory for improving forecasting of marine carbon sequestration rates, working to integrate this new framework into the models that are currently used for forecasting carbon stocks in the ocean, and exploring the potential impacts that other variables, such as ecosystem size, might have on their theory.

APPENDIX A
RESEARCH PROJECTS

Blue Carbon

PI:

- Peter Raymond, Professor and Senior Associate Dean of Research at the School of the Environment and Professor of Earth and Planetary Science

RESEARCHERS AT YALE:

- Derrick Vaughn, Postdoctoral Researcher
- Sophia Chirico, Postgraduate Associate
- Naomi Norbraten, Undergrad

COLLABORATORS AT OTHER INSTITUTIONS:

- Alfia Ansari, Southern Connecticut University
- Eugenia Apostolaki, Hellenic Centre for Marine Research (Greece)
- Pavlos Efthymiadis, Hellenic Centre for Marine Research (Greece)
- Angelo Bernadino, Universidade Federal do Espirito Santo (Brazil)
- Thomas Bianchi, University of Florida
- Elise Morrison, University of Florida
- Joshua Breithaupt, Florida State University
- Anthony Campbell, NASA
- Edward Castenada, Miami-Dade Division of Environmental Resources Management
- Holly East, Northumbria University (UK)
- Stephanie Helber, Northumbria University (UK)
- Sean Fitzpatrick, West Africa Blue (Africa)
- Allison Hoyt, Stanford University
- Julie Shahan, Stanford University
- Nicolas Moity, Charles Darwin Foundation (Galapagos)
- Hannah Morrisette, Smithsonian Environmental Research Center
- Ninon Martinez, Smithsonian Environmental Research Center
- Dorothy Peteet, Lamont-Doherty Earth Observatory
- Clara Chang, Lamont-Doherty Earth Observatory
- Sigit Sasmito, James Cook University (Australia)
- Craig Smeaton, St. Andrews University (UK)
- Amanda Spivak, University of Georgia
- Salvatrice Vizzini, University of Palermo (Italy)
- Laura Caviglia, University of Palermo (Italy)
- Lisa Windham-Myers, USGS
- Giovanna Wolswijk, Universite Libre de Bruxelles (Brussels)

APPENDIX A
RESEARCH PROJECTS

PROJECT OVERVIEW:

The Blue Carbon project aims to investigate how carbon flows within coastal systems, including mangrove forests, salt marshes, and seagrass meadows. The project seeks to understand the amount of carbon and other greenhouse gasses stored in different components of these ecosystems and for how long.

This research is significant because these systems are increasingly impacted by human activities, such as coastal development, and climate change itself, through extreme weather events. Despite their importance in providing economic benefits and services such as storm surge protection, water filtration, and support for fisheries, scientists still lack a comprehensive understanding of carbon dynamics and storage within these ecosystems. This project seeks to fill this knowledge gap and contribute to a better understanding of coastal ecosystems' role in carbon sequestration and climate change mitigation

RECENT PROGRESS:

- The team has worked in Florida and Massachusetts to measure alkalinity produced by blue carbon ecosystems – the process by which carbon from blue carbon ecosystems is flushed into the sea and stored for long periods of time as carbonates. This feature of blue carbon is not well studied but is critical to understanding total carbon sequestration capacity. Based on data collected to date, and further data to be collected in the future, the team is modeling this important component to test how it will impact the total carbon sequestration rates of blue carbon remediation and restoration projects.
- The team is also developing an affordable tool to measure alkalinity in the field. The instrument, which is made of multiple pumps, valves, and a sophisticated electronics system, has undergone laboratory and initial field tests and has received a provisional patent. A $30,000 grant from the U.S. Geological Survey (USGS) has been secured to further develop this novel instrument.

GEOLOGICAL AND OCEAN CAPTURE: ENHANCED ROCK WEATHERING (ERW)
Harnessing Natural Basalt Weathering to Capture CO_2 in Agricultural Settings

PIs:

- Noah Planavsky, Associate Professor of Earth & Planetary Sciences
- Jim Saiers, Clifton R. Musser Professor of Hydrology
- Pete Raymond, Senior Associate Dean of Research & Director of Doctoral Studies; Oastler Professor of Biogeochemistry
- Yuan Yao, Associate Professor of Industrial Ecology and Sustainable Systems

RESEARCHERS AT YALE:

- Boriana Kalderon-Asael, Research Assistant
- Marya Matlin-Wainer, Postgraduate Associate
- Fengchao Sun, Postdoctoral Researcher
- Aaron McDonald, Postgraduate Associate
- Esmeralda Garcia, Postgraduate Associate
- Wyatt Tatge, PhD Student
- Robbie Rioux, PhD Student
- Quinn Zacharias, PhD Student

APPENDIX A
RESEARCH PROJECTS

- Jiuyuan Wang, Postdoctoral Researcher
- Jesper Suhrhoff, Postdoctoral Researcher
- Evelin Pihlap, Postdoctoral Researcher
- Bingquan Zhang, Postdoctoral Researcher
- Ayesha Ahmed, Graduate Student
- Brian Beaty, PhD Student
- Isabella Chiaravalloti, PhD Student
- Chloe Kent, Graduate Student
- Jennifer Kroeger, PhD Student
- Tom Reershemius, PhD Student
- Gavrielle Welbel, Research Fellow
- Juan Lora, Assistant Professor of Earth & Planetary Sciences
- Kaylea Nelson, Director, Arts & Sciences Research Computing

COLLABORATORS AT OTHER INSTITUTIONS:

- David J. Beerling: Professor of Natural Sciences, University of Sheffield
- Yoshiki Kanzaki: Postdoctoral Researcher, School of Earth & Atmospheric Sciences, Georgia Institute of Technology
- Chiristopher T. Reinhard, Associate Professor, Georgia Institute of Technology
- Shuang Zhang, Assistant Professor, Texas A&M
- Charles Driscoll, Professor, Syracuse University

PROJECT OVERVIEW:

This project is exploring the potential of carbon dioxide removal (CDR) in agricultural lands and developing methods to track and quantify ERW strategies to ensure durable CDR. Researchers are conducting field trials where ground-up minerals are added to fields growing different crops. They will then measure carbon uptake rates via plant productivity, soil carbon storage, and downstream transport through watersheds to the ocean. Laboratory analyses and a review of existing scientific literature will complement the field trials.

RECENT ACCOMPLISHMENTS:

- The team has demonstrated carbon capture through ERW at a greater than 10-ton scale over multiple years and conducted an exploration of how enhanced weathering affects soil structure, moisture retention, and drought resistance.
- Based on its work to date, the team is collaborating with Microsoft, FedEx, and Frontier Climate Fund to produce recommendations for ERW best practices. The team is also working on a project with Microsoft to conduct an academic evaluation of specific ERW efforts.
- To date, the team has secured over $10 million in ERW grants and gifts from USDA, Google, the Grantham Foundation, and DOE.
- The team conducted a whole-watershed application of 450 tonnes of crushed basalt on pasture and hayfield in Vermont. The basalt application was completed in June 2023. Hydrological, geochemical, and biological measurements were initiated in 2022 following installation of a groundwater-monitoring array, automated surface-water samplers, and streamflow instrumentation. Increases in stream water alkalinity demonstrating carbon-dioxide removal by basalt weathering have been observed and are currently being quantified.

APPENDIX A
RESEARCH PROJECTS

- The team continued development of instrumentation for measuring CO_2 removal by ERW, with a newly developed AutoLysimeter. This instrument enables accurate determination of soil-water and weathering-product fluxes over a range of soil-moisture conditions. It can be rapidly deployed at low cost and with minimal site disturbance.
- The team partnered with Connecticut Land Trusts and identified several Land Trusts interested in hosting ERW field trials. Site selection will begin in fall 2024 with plans to begin ERW trials in spring 2025.

SCIENTIFIC PUBLICATIONS:

Published:

- Baek, S.H., Kanzaki, Y., Lora, J.M., Planavsky, N., Reinhard, C.T., Zhang, S., 2023. Impact of Climate on the Global Capacity for Enhanced Rock Weathering on Croplands. Earths Future 11(8). doi.org/ARTN e2023EF00369810.1029/2023EF003698.
- Beerling, D.J., Epihov, D.Z., Kantola, I.B., Masters, M.D., Reershemius, T., Planavsky, N.J., Reinhard, C.T., Jordan, J.S., Thorne, S.J., Weber, J., Martin, M.V., Freckleton, R.P., Hartley, S.E., James, R.H., Pearce, C.R., DeLucia, E.H., Banwart, S.A., 2024. Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits. P Natl Acad Sci USA 121(9). doi.org/ARTN e231943612110.1073/pnas.2319436121.
- Chiaravalloti, I., Theunissen, N., Zhang, S., Wang, J.Y., Sun, F.C., Ahmed, A.A., Pihlap, E., Reinhard, C.T., Planavsky, N.J., 2023. Mitigation of soil nitrous oxide emissions during maize production with basalt amendments. Front Clim 5. doi.org/ARTN 120304310.3389/fclim.2023.1203043.
- Fakhraee, M., Li, Z.J., Planavsky, N.J., Reinhard, C.T., 2023a. A biogeochemical model of mineral-based ocean alkalinity enhancement: impacts on the biological pump and ocean carbon uptake. Environ Res Lett 18(4). doi.org/ARTN 04404710.1088/1748-9326/acc9d4.
- Fakhraee, M., Planavsky, N.J., Reinhard, C.T., 2023b. Ocean alkalinity enhancement through restoration of blue carbon ecosystems. Nat Sustain. doi.org/10.1038/s41893-023-01128-2.
- Fakhraee, M., Tarhan, L.G., Reinhard, C.T., Planavsky, N.J., 2023d. Constraining the elemental stoichiometry of early marine life. Geology 51(11), 1043-1047. doi.org/10.1130/G51416.1.
- Kanzaki, Y., Chiaravalloti, I., Zhang, S., Planavsky, N.J., Reinhard, C.T., 2024. In silico calculation of soil pH by SCEPTER v1.0. Geosci Model Dev 17(10), 4515-4532. doi.org/10.5194/gmd-17-4515-2024.
- Kanzaki, Y., Planavsky, N.J., Reinhard, C.T., 2023. New estimates of the storage permanence and ocean co-benefits of enhanced rock weathering. Pnas Nexus 2(4). doi.org/10.1093/pnasnexus/pgad059.
- Kanzaki, Y., Zhang, S., Planavsky, N.J., Reinhard, C.T., 2022. Soil Cycles of Elements simulator for Predicting TERrestrial regulation of greenhouse gases: SCEPTER v0.9. Geosci Model Dev 15(12), 4959-4990. doi.org/10.5194/gmd-15-4959-2022.
- Reershemius, T., Kelland, M.E., Jordan, J.S., Davis, I.R., D'Ascanio, R., Kalderon-Asael, B., Asael, D., Suhrhoff, T.J., Epihov, D.Z., Beerling, D.J., Reinhard, C.T., Planavsky, N.J., 2023. Initial Validation of a Soil-Based Mass-Balance Approach for Empirical Monitoring of Enhanced Rock Weathering Rates. Environ Sci Technol 57(48), 19497-19507. doi.org/10.1021/acs.est.3c03609.
- Reinhard, C.T., Planavsky, N.J., Khan, A., 2023. Aligning incentives for carbon dioxide removal. Environ Res Lett 18(10). doi.org/ARTN 10100110.1088/1748-9326/acf591.
- Suhrhoff, T.J., Reershemius, T., Wang, J.Y., Jordan, J.S., Reinhard, C.T., Planavsky, N.J., 2024. A tool for assessing the sensitivity of soil-based approaches for quantifying enhanced weathering: a US case study. Front Clim 6. doi.org/ARTN 134611710.3389/fclim.2024.1346117.

APPENDIX A
RESEARCH PROJECTS

- Wang, J.Y., Di, Y.K., Asael, D., Planavsky, N.J., Tarhan, L.G., 2023a. An investigation of factors affecting high-precision Sr isotope analyses (87Sr/86Sr and δ88/86Sr) by MC-ICP-MS. Chem Geol 621. doi.org/ARTN 12136510.1016/j.chemgeo.2023.121365.
- Wang, J.Y., Tarhan, L.G., Jacobson, A.D., Oehlert, A.M., Planavsky, N.J., 2023b. The evolution of the marine carbonate factory. Nature 615(7951), 265-+. doi.org/10.1038/s41586-022-05654-5.
- Zhang, B.Q., Kroeger, J., Planavsky, N., Yao, Y., 2023a. Techno-Economic and Life Cycle Assessment of Enhanced Rock Weathering: A Case Study from the Midwestern United States. Environ Sci Technol 57(37), 13828-13837. doi.org/10.1021/acs.est.3c01658.
- Zhang, F.F., Stockey, R.G., Xiao, S.H., Shen, S.Z., Dahl, T.W., Wei, G.Y., Cao, M.C., Li, Z.H., Kang, J.Y., Cui, Y., Anbar, A.D., Planavsky, N.J., 2022. Uranium isotope evidence for extensive shallow water anoxia in the early Tonian oceans. Earth Planet Sc Lett 583. doi.org/ARTN 11743710.1016/j.epsl.2022.117437.
- Zhang, S., Planavsky, N.J., Katchinoff, J., Raymond, P.A., Kanzaki, Y., Reershemius, T., Reinhard, C.T., 2022. River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering. Limnol Oceanogr 67, S148-S157. doi.org/10.1002/lno.12244.

Calibrating Enhanced Rock Weathering with Os and Sr Isotopes

PIs:

- Alan Rooney, Assistant Professor of Earth & Planetary Sciences
- Drew Syverson, Research Assistant Professor, UNC Charlotte

RESEARCHERS AT YALE:

- Carey Ciaburri, Graduate Student

COLLABORATORS AT OTHER INSTITUTIONS:

- Sarah Holloway, Graduate Student, UNC Charlotte
- Logan Brooks, Graduate Student, UNC Charlotte

PROJECT OVERVIEW:

One of the most promising ERW approaches is the addition of a very common basalt rock in the form of powder to agricultural fields – a process that has the potential to both increase crop yields and actively remove greenhouse gasses from the atmosphere. However, the ability to accurately track how much CO_2 is removed through this process is still an active area of research and further validation is needed before it can be deployed at scales necessary to become a meaningful climate mitigation strategy.

This project combines field site studies, laboratory experiments, and modeling of chemical reactions in order to more accurately quantify the rate and efficiency of atmospheric CO_2 removal using this approach, as well as to identify any practical limitations. Data generated by this project will help to identify the parameters necessary for the most cost-effective and efficient ways to leverage this approach to remove CO_2 from the atmosphere.

APPENDIX A
RESEARCH PROJECTS

RECENT ACCOMPLISHMENTS:

- The team conducted a geochemical analysis of waters and feedstocks from a site in Illinois, with a focus on the neodymium (Nd), osmium (Os), and strontium (Sr) systems – the elements with which the transfer of carbon through various reactions can be traced. Using this analysis, the team developed geochemical modeling structures to determine reactions over a range of timescales, which will better inform the understanding of carbon sequestration rates.
- The team has also conducted laboratory experiments at UNC to better understand the potential of neodymium (Nd), osmium (Os), and strontium (Sr) as tracers to quantify enhanced mineral weathering in natural environments.

Evaluation of Modeling Approaches for Enhanced Weathering

PI:

- Edward W. Bolton, Senior Research Scientist, Department of Earth and Planetary Sciences

RESEARCHERS AT YALE:

- Noah Planavsky, Associate Professor, Department of Earth and Planetary Sciences

COLLABORATORS AT OTHER INSTITUTIONS:

- David J. Beerling: Sorby Professor of Natural Sciences, School of Biosciences, University of Sheffield
- Lyla Tavlor, Senior Research Fellow, School of Biosciences, University of Sheffield
- Mark Lomas, Research Associate, School of Mathematics and Statistics, University of Sheffield
- Chris Reinhard, Associate Professor, Georgia Tech
- Yoshiki Kanzaki: Postdoctoral Researcher, School of Earth & Atmospheric Sciences, Georgia Tech

PROJECT OVERVIEW:

Various scientific models have been designed to predict and estimate the amount of carbon captured and stored through ERW on agricultural lands, which is key to understanding the actual climate impact of such efforts. These different modeling efforts, however, have produced a wide range of CO_2 removal estimates, and the root cause for this variation is not clear.

This project uses exploratory pilot research to compare these models with the goal of determining what factors lead to the differences in CO_2 removal estimates. In turn, this will help to refine predictions and better inform ERW efforts as a scalable means of carbon capture and sequestration. Areas of exploration include a wide range of soil conditions, temperature, as well as the mineralogy and grain-size distributions of crushed basalts applied to agricultural soils. The project will compare results over the course of a year, measuring daily rainfall and temperature to assess the influence of these conditions. Researchers will also assess factors – such as the influence of heterogeneities in the soil permeability field – beyond what current models consider.

APPENDIX A
RESEARCH PROJECTS

RECENT ACCOMPLISHMENTS:

- The team has made considerable progress in evaluating ERW modeling approaches. Using the Kinflow reactive transport model, developed by Dr. Bolton, the team has been able to accurately measure the amount of biologic and nonbiologic CO_2 captured across a number of variables.
- The team has also made progress advancing its RockMIP project, which focuses on comparing enhanced weathering reactive transport models and establishing a consensus on the models to be used for estimating carbon capture and storage rates.
- The team also conducted sporadic rainfall studies, which showed significant changes in the amount of CO_2 captured, even when the average rainfall rate was the same. These findings were presented at the Fall 2023 AGU conference and are being prepared for publication.
- Another study conducted by the team, and presented at ERW24 at Yale, showed secondary minerals used in conjunction with balasalt may have little overall effect on the amount of CO_2 captured.

Building a Theoretical Framework to Assess the Realistic Potential for In Situ Carbon Mineralization

PI:

- Jun Korenaga, Professor of Earth & Planetary Sciences

PROJECT OVERVIEW:

This project aims to understand the often overlooked processes of confining pressure, which results from the weight of overlaid rocks, on the ability of in situ mineralization processes to capture and store carbon. The project will develop a new theoretical framework to address the impact of confining pressure on the feedback between permeability and chemical reactions. One-dimensional reactive transport models are used to explore various possibilities by varying water transport mode, permeability model, and the relation between porosity and elastic strain energy. The results will provide insights into engineering possibilities and assist in life cycle analyses for potential in situ carbon mineralization solutions, advancing the understanding and application of this approach for CO_2 removal and sequestration.

RECENT ACCOMPLISHMENTS:

- The team has developed a new theoretical framework to determine the maximum extent of carbonation in geological materials without relying on crystallization pressure – something that has been elusive in other studies of this issue. This new framework introduces the concept of a critical depth to determine the bounds within which carbonation can occur. Using this framework, the team determined that below a critical depth of ~1km, carbonation is unlikely to occur. Based on this, it is likely that shallow, porous basal reservoirs present the most promising reservoir type for carbonation.
- This theory also exposes the ambiguity of aspects of current models, and provides a framework by which to improve them. The theory will be useful for synergizing laboratory experiments, field-scale experiments, and geological records to better assess the storage potential of different geological reservoirs. It will also have important implications for current efforts to combine ERW with the mining of critical metals.

APPENDIX A
RESEARCH PROJECTS

GEOLOGICAL AND OCEAN CAPTURE: OCEAN ALKALINITY ENHANCEMENT
Investigating the Role of Ocean Processes in mCDR

PI:

- Mary-Louise Timmermans, Damon Wells Professor of Earth and Planetary Sciences, Director of Graduate Studies, Department of Earth & Planetary Sciences

RESEARCHERS AT YALE:

- Adam Yang, Postdoctoral Researcher
- Yiming Guo, Postdoctoral Researcher

SCIENTIFIC PUBLICATIONS:

Published:

- Guo, Y., and M.-L. Timmermans, 2024. The role of ocean mesoscale variability in air-sea CO_2 exchange: A global perspective. Geophysical Research Letters, 51, e2024GL108373.https://doi.org/10.1029/2024GL108373.
- Guo, Y., and M.-L. Timmermans, 2024. Global Ocean pCO_2 variation regimes: spatial patterns and the emergence of a hybrid regime. Journal of Geophysical Research, https://doi.org/10.1029/2023JC020679.
- Yang, J.K. and M.-L. Timmermans, 2024. Assessing the effective settling of mineral particles in the ocean with application to ocean-based carbon-dioxide removal. Environmental Research Letters, https://doi.org/10.1088/1748-9326/ad2236.
- Yang, J.K., M.-L. Timmermans, and G.A. Lawrence, 2024. Asymmetric Kelvin-Helmholtz instabilities in stratified shear flows. Phys. Rev. Fluids 9, https://doi.org/10.1103/PhysRevFluids.9.014501.
- Yang, J.K., J. Olsthoorn, M.-L. Timmermans, 2023. Sedimentation in particle-laden flows with and without velocity shear. Physics of Fluids, 35 (8), https://doi.org/10.1063/5.0159676.

PROJECT OVERVIEW:

The project studies how the varying and energetic motions in the ocean's surface impact its ability to absorb carbon and the effectiveness of mCDR methods, such as adding milled mineral particles to the surface of the ocean. The project focuses on understanding how ocean flows, temperature, and layers affect the exchange of carbon dioxide between the air and sea, which is essential for assessing the ocean's role in the carbon cycle and its carbon storage capacity. The research uses numerical modeling, theory, and observational analysis to explore global ocean carbon variability and assess how sediment concentrations change in active marine environments.

RECENT ACCOMPLISHMENTS:

- By investigating the variability and drivers of carbon dioxide exchange between the atmosphere and ocean on a global scale, the team has found a new variable that impacts this exchange. While previous studies have suggested the exchange may be governed by one of two main ocean parameters – sea surface temperature or dissolved inorganic carbon – the team has discovered that seasonally varying factors can be associated with anomalously high CO_2 uptake rates. The research has also shown that the orientation of small-scale ocean motions, such as strong eddying motions and other energetic currents, in relation to the background distribution of carbon in the ocean can lead to a significant gain or loss of CO_2 captured at the regional level. These findings have implications for understanding the ocean's ability to absorb and store carbon in different regions, and

APPENDIX A
RESEARCH PROJECTS

how that might change in the future based on a number of variables.

- The team has also made progress to better understand and quantify the carbon dioxide removal potential of adding milled mineral particles to the ocean. The method's success depends on how long the particles stay in the surface ocean to dissolve, which is influenced by how fast they settle. Typically, settling rates are measured under still conditions. However, the team's research found that in a moving, layered ocean setting, this settling rate can vary significantly, in some cases causing particles to settle up to ten times faster. These findings highlight the need to consider different marine conditions to optimize CO_2 removal strategies.

An Integrated Biorefinery Pathway for CO_2 into Value-Added Materials via Biologic Carbon Fixation and Carbonate Precipitation

PI:

- Shu Hu, Assistant Professor of Chemical & Environmental Engineering

RESEARCHERS AT YALE:

- Prof. Julie B. Zimmerman, Professor of Green Engineering, Yale School of the Environment & Dept. of Chemical and Environmental Engineering, Deputy Director of the Center for Green Chemistry and Green Engineering
- Prof. Paul T. Anastas, Teresa and H. John Heinz III Professor in the Practice of Chemistry for the Environment, School of the Environment & School of Public Health, Director of the Center for Green Chemistry and Green Engineering
- Momoko Ishii, PhD Candidate
- Atsu Kludze, PhD Student
- Marcelo Lejeune, Undergraduate Student

SCIENTIFIC PUBLICATIONS:

Published:

- Atsu Kludze†, Devan Solanki†, Marcelo Lejeune, Rito Yanagi, Momoko Ishii, Neera Raychaudhuri, Paul Anastas, Nanette Boyle, Shu Hu, iScience, 105156. Biocement from the ocean: Hybrid microbial-electrochemical mineralization of CO2. DOI:10.1016/j.isci.2022.105156

PROJECT OVERVIEW:

This project aims to explore a novel approach for CO_2 removal from the atmosphere using ocean-based carbon capture strategies. The ocean's natural ability to sequester carbon through dissolved inorganic carbon (DIC) is leveraged by adjusting the ocean's pH to promote enhanced dissolved inorganic carbon removal. This involves converting bicarbonate and carbonate into dissolved gaseous CO_2 for extraction and processing or facilitating dissolved inorganic carbon removal through the precipitation of carbonate minerals like calcite. The project focuses on using microbially induced carbonate precipitation (MICP) by employing cyanobacteria as biological nucleation seeds for accelerated calcite precipitation. The goal is to develop an integrated biorefinery strategy that uses microbially induced carbonate precipitation and cyanobacteria to produce carbonate-encapsulated cyanobacteria, creating a valuable end product while sequestering CO_2 from the ocean. The success of this work

APPENDIX A
RESEARCH PROJECTS

could offer insights into a hybrid approach combining microbial photosynthesis and microbially induced carbonate precipitation for oceanic carbon fixation and its potential application for large-scale carbon capture and utilization.

RECENT ACCOMPLISHMENTS:

- The team published a perspective paper that discusses an ocean-based, microbial-electrochemical approach for simultaneous carbon fixation and carbonate precipitation enhanced via bipolar membrane electrodialysis devices.
- The team demonstrated atomic layer deposition (ALD) growth on membranes, determined ALD membrane design principles, and revealed that the membranes currently being used are too electronically resistive.
- Going forward the team is focusing on further advancing membrane design as well as growing and analyzing cyanobacteria with high CO_2 sequestration potential.

INDUSTRIAL CARBON UTILIZATION
Capturing CO_2 from Dilute Sources for Chemical Catalysis

PI:

- Nilay Hazari, John Randolph Huffman Professor of Chemistry and Chair, Department of Chemistry

RESEARCHERS AT YALE:

- Young Hyun Hong, Postdoctoral Researcher
- Matthew Elsby, Postdoctoral Researcher
- Abhishek Kumar, Postdoctoral Researcher

SCIENTIFIC PUBLICATIONS:

Published:

- Espinosa, M. R.; Ertem, M. Z.; Barakat, M.; Bruch, Q. J.; Deziel,
- A. P.; Elsby, M. R.; Hasanayn, F.; Hazari, N.; Miller, A. J.M.; Pecoraro, M. V.; Smith, A.; Smith, N. E. Correlating Thermodynamic and Kinetic Hydricities of Rhenium Hydrides.
- J. Am. Chem. Soc. 2022, 144, 17939-17954.
- Deziel, A. P.; Gahlawat, S.; Hazari, N.; Hopmann, K. H.; Mercado, B. Q. Comparative Study of CO2 Insertion into Pincer Supported Palladium Alkyl and Aryl Complexes. Chem. Sci. 2023, 14, 8164-8179.
- Elsby, M. R.; Espinosa, M. R.; Ertem, M. Z.; Deziel, A. P.;
- Hazari, N.; Miller, A. J. M.; Paulus, A. H.; Pecoraro, M. V. Carbon Dioxide Insertion into Rhenium Hydrides as a Probe for the Impact of Solvent on Linear Free Energy Relationships Between Thermodynamic and Kinetic Hydricity. Organometallics, 2023, 42,3005-3012.

PROJECT OVERVIEW:

The project looks at converting CO_2 into more valuable products, such as plastics or fuels, with a goal of informing the design of practical applications. To facilitate the transformation of CO_2 to value-added products, new catalysts are required that can activate CO_2, which is typically an unreactive molecule. This project focuses specifically on metal catalysts, which are highly

APPENDIX A
RESEARCH PROJECTS

reactive and can readily be tuned. This project has two key areas of research:

1) Understanding how CO_2 interacts with transition metals. The project explores how changing the metal or solvent type affects the reaction rate with CO_2. This research will help develop better catalysts for CO_2 conversion and guide future catalyst design.
2) Making existing CO_2 conversion catalysts more practical. The project aims to transform homogeneous catalysts, which are selective and tunable but not practical, into heterogeneous catalysts, which are more practical, by attaching them to a silicon-based support. The project is also seeking to transform catalysts powered by electricity into ones powered by natural sunlight by leveraging silicon's light-capturing properties.

RECENT ACCOMPLISHMENTS:

- The team succeeded in creating a highly active and selective photoelectrocatalyst for converting CO_2 to formate by attaching a molecular manganese (Mn) catalyst with a silatrane functional group to thermally oxidized porous silicon (Si). This is significant because few systems can selectively reduce CO_2 to formate and it introduces porous Si as a new light-absorbing support for molecular catalysts. The team is preparing a manuscript related to these findings and is in the process of filing for a provisional patent for the system.
- The team has also conducted studies related to the kinetics and thermodynamics of CO_2 insertion into transition metal hydrides, which could help to design more selective catalysts.
- The team has also contributed to a project that explores CO_2 insertion into palladium alkyl complexes – a fundamental step in catalytic cycles that form C-C bonds from CO_2.

Developing CO_2 Electrolyzers for Methanol Production

PI:

- Hailiang Wang, Professor of Chemistry, Department of Chemistry

RESEARCHERS AT YALE:

- Seonjeong Cheon, Postdoctoral Researcher
- Chungsuk Choi, Postdoctoral Researcher
- Jing Li, Postdoctoral Researcher
- Qi Sun, Associate Research Scientist
- Conor Rooney, Graduate Student

COLLABORATORS AT OTHER INSTITUTIONS:

- Stafford Sheehan, Air Co.

SCIENTIFIC PUBLICATIONS:

Published:
- Jing Li, Bo Shang, Yuanzuo Gao, Seonjeong Cheon, Conor L. Rooney, Hailiang Wang, "Mechanism-Guided Realization of

APPENDIX A
RESEARCH PROJECTS

Selective Carbon Monoxide Electroreduction to Methanol", Nat. Synth. 2023, 2, 1194-1201.
- Seonjeong Cheon, Jing Li, Hailiang Wang, "In-Situ Generated CO Enables High-Current CO2 Reduction to Methanol in a Molecular Catalyst Layer", J. Am. Chem. Soc. 2024, DOI: 10.1021/jacs.4c05961

PROJECT OVERVIEW:

Existing processes can efficiently convert CO_2 into useful products like carbon monoxide, formic acid, methane, or ethylene. However, converting CO_2 to methanol, a valuable chemical and fuel, is challenging due to the lack of effective catalysts. This project has developed the first molecular electrocatalyst that can significantly produce methanol from CO_2. This breakthrough paves the way for new electrochemical CO_2-to-methanol technology.

The project's goal is to establish a solid scientific foundation to make this catalytic reaction a viable technology, potentially outperforming or complementing natural processes. A main objective is to develop a small-scale electrolyzer that can efficiently convert CO_2 to methanol with high selectivity, fast reaction rate, and stable operation. Achieving this will help to make more viable methanol production from CO_2 using renewable electricity.

RECENT ACCOMPLISHMENTS:

- The team has continued to advance the chemistry, materials, and reactor engineering to improve the CO2 to methanol conversion process initially discovered by this project. The team is working to meet the requirements for an emerging sustainable liquid fuel production technology.
- The team has overcome a key limiting step of CO_2-to-methanol conversion, and has developed a viable system for practical application.
- The team filed a patent application for their technology, which is being licensed by a newly-formed company (Oxylus Energy) to further develop and commercialize the technology. Oxylus Energy has raised $4.5 million (led by Toyota) for its efforts.

Development of Plasma Electrolysis for CO_2 Activation and Selective Upgrading

PI:

- Lea Winter, Assistant Professor of Chemical and Environmental Engineering
- Hailiang Wang, Professor of Chemistry

RESEARCHERS AT YALE:

- Ji-Yong Kim, Postdoctoral Researcher
- Julia Simon, Graduate Student
- Kelby Anderson, Graduate Student
- Saachi Grewal, Undergraduate Student
- Andy Park, Undergraduate Student
- Jacob Simmons, Undergraduate Student
- Yana Eber, Undergraduate Student

APPENDIX A
RESEARCH PROJECTS

COLLABORATORS AT OTHER INSTITUTIONS:

- Annemie Bogaerts, University of Antwerp
- Omar Biondo, University of Antwerp

SCIENTIFIC PUBLICATIONS:

Published:

- Lea R. Winter, Jingguang G. Chen. "Challenges and opportunities in plasma-activated reactions of CO_2 with light alkanes." Journal of Energy Chemistry 84: 424–427 (2023). DOI: 10.1016/j.jechem.2023.05.038
- Claire Butler, Yingzheng Fan, Saachi Grewal, Lea R. Winter. "At-field and on-demand nitrogenous fertilizer synthesis." ACS Sustainable Chemistry & Engineering 11 (15): 5803–5818 (2023). DOI: 10.1021/acssuschemeng.2c06551

PROJECT OVERVIEW:

This project focuses on developing innovative technologies to convert CO_2 into valuable chemicals and fuels, which can replace conventional fossil fuel-based processes that emit large amounts of CO_2. By combining plasma reactions and electrochemical conversion, the researchers aim to activate CO_2 under mild conditions and produce higher-value compounds. They seek to create a technology that directly converts CO_2 into more complex products, like propylene and propanol, which are valuable as fuels. The project aims to achieve this in a sustainable and energy-efficient manner, contributing to a carbon-neutral energy cycle and further reducing greenhouse gas emissions.

RECENT ACCOMPLISHMENTS:

- The team has established two new reactor systems to demonstrate the first example of plasma-electrocatalytic CO_2 conversion, including generation of novel and high-value products. A provisional patent is being prepared for this work.
- The team has demonstrated how plasma activation of CO_2 can improve conversion efficiency and boost reaction rates for generation of multi-carbon products. They have also shown how plasma activation can unlock unique products that are only produced when this activation is used.
- The team has also conducted experiments to better understand the role of plasma-activated water in CO_2 conversion reactions. Results so far reveal that plasma activation increases the generation of multi-carbon products and could lead to the creation of new products such as acetone and acetaldehyde.
- Through their research, the team is continuing to gain a deeper understanding of these processes with the goal of better controlling the generation of high-value products.

APPENDIX A
RESEARCH PROJECTS

Storing CO_2 in the Form of Sustainable Materials

PI:

- Mingjiang Zhong, Assistant Professor of Chemical & Environmental Engineering and Chemistry

RESEARCHERS AT YALE:

- Yinan Chen, Graduate Student
- Dr. Junwoo Lee, Research Scientist
- Yazhen Xue, Graduate Student

PROJECT OVERVIEW:

The project aims to leverage CO_2 to produce high value materials as well as to replace traditional high-emissions inputs. The researchers are working to find innovative and efficient ways to turn CO_2 into high-value and robust plastics that can be easily broken down and re-used in order to create a circular economy for these products. The project is also exploring ways to directly transform CO_2 into basic building blocks for various materials that are traditionally produced with high-emission processes, thereby reducing emissions associated with their development and manufacture.

RECENT ACCOMPLISHMENTS:

- The team explored the substrate scope for reductive CO_2 copolymerization via 4-electron reduction and managed to synthesize polythioacetals with high molecular weight. (up to 40kDa) The derived polymer has been characterized through various calorimetrical and spectroscopic methods. The detailed structure and mechanical properties have been analyzed.
- The team synthesized A series of dual-site catalysts based on Salen/porphyrin structures with pendant functional groups. Metal centers and organoboron centers have been strategically selected and incorporated to create dual-site catalysts. However, we found the metal centers with a high oxidative state, like Co(III), Cr(III) could not be compatible with the organoboron center. Oxidation reaction will simultaneously occur with the incorporation of organoboron centers. Hence, the synergistic effect between the metal center and the boron center failed to be accomplished. The Lewis acidity of organoboron compounds and the catalytical activity in ROCOP have then been thoroughly investigated.
- The team has designed and synthesized acid-stable Cu cluster precatalysts that are in-situ reduced into active Cu nanoparticles in strong acid. Operando Raman and X-ray spectroscopies indicate that the bonding between the ligand of the Cu cluster precatalyst and in-situ formed Cu nanoparticles preserved a high density of undercoordinated Cu sites, which led to the high C_2+ Faradaic efficiency. The catalysts achieved a C_2H_4 Faradaic efficiency of 57% at 100 mA/cm2, which translated into an improvement of 1.4x in energy efficiency compared to the most efficient prior acidic CO_2– to C_2+ electrocatalytic systems.

APPENDIX B

YCNCC-ENDOWED FACULTY

DETAILED FY24 UPDATES

Dr. Paulo Brando

CURRENT RESEARCH FOCUS

Deforestation and forest degradation in the Amazon

WEBSITE: https://campuspress.yale.edu/brandolab/

LAB GROUP:

1 Research Scientist; 2 Postdoctoral Researchers; 3 PhD Students; 1 Masters Student; 2 Research Associates

SELECTED PUBLICATIONS:

- Ribeiro AF, Santos, L, Randerson JT, Uribe MR, Alencar AA, Macedo MN, Morton DC, Zscheischler J, Silvestrini R, Rattis L, Seneviratne SI and Brando PM. (2024). The time since land-use transition drives changes in fire activity in the Amazon-Cerrado region. *Communications Earth & Environment, 5*(1), 96.
- Brando PM, Silvério DV, Maracahipes L, Benzi R, Paolucci LN, Maracahipes-Santos L, Rattis L, Macedo M, and Balch JK. (2024) Legacies of Multiple Disturbances on Fruit and Seed Patterns in Amazonia: Implications for Forest Functional Traits. *Ecosphere* 15(2): e4780.
- Ribeiro VS, Schoereder JH, Sobrinho TG, Brando PM, Maracahipes-Santos L, Macedo MN. et al. (2024) Ecosystem functions of ants and dung beetles in agriculture-dominate
- Li Y, Baker JC, Brando PM, Hoffman FM, Lawrence DM, Morton DC, Swann AL, Uribe MD***, Randerson JT (2023) Future increases in Amazonia water stress from CO2 physiology and deforestation. *Nature Water*. 31:1-9.
- Uribe M, Coe M, Castanho A, Macedo M, Valle D, Brando PM (2023) Net Loss of Biomass Predicted for Tropical Biomes in a Changing Climate. *Nature Climate Change*.

SELECTED OUTREACH:

- Managing Tropical Ecosystems for Climate Change Solutions – Invited speaker, YSE Leadership Meeting, Yale University, New Haven, CT, September, 2023
- The Future of Amazonian Forests – Invited speaker, 2023 Lovejoy Symposium, World Wildlife Fund, Washington, DC, October 17, 2023
- Forests in a Changing Climate: Greenhouse Gas Source or Sink – Invited panelist, The Forest Dialogue Steering Committee, Yale University, New Haven, CT, February 1, 2024
- A Synthesis of Twenty Years of Ecological Research in Southeast Amazonia and a Glimpse of How to Avoid Future Loss of Forests' Trees to Wildfires, Droughts, and Fragmentation – Speaker and YCNCC representative, Tanguro Science Symposium, Brasilia, Brazil, July 10-12, 2024
- Amazonian Forests and Global Changes – Invited speaker, Yale Institute for Biospheric Studies (YIBS) Leadership, Yale University, New Haven, CT, April, 2024
- What Will Happen to Amazon Forests with Climate Change? – Invited speaker and visitor, McMillan Center, Rio de Janeiro, Brazil, May, 2024

APPENDIX B

YCNCC-ENDOWED FACULTY

GRANTS:

Funder: National Science Foundation; Amount awarded: $2.5 million; Period of performance: 2024-2028; Title: Biodiversity of a Changing Planet: Living on The Edge: Plant-Animal Interactions and the Cascading Impacts of Amazon Forest Fragmentation

Funder: NASA; Amount awarded: $1.3 million; Period of performance: 2023-2027; Title: Amazon Wildfires: Improving Fire Risk Forecasting to Mitigate Impacts on Forest Ecosystems and Human Health

Funder: National Science FoundationAmount awarded: $599,877; Period of performance: 2021-2026; Title: LTREB: Legacy Effects of Compounding Disturbances in the Amazon: Implications for Ecosystem Carbon and Water Cycling

Funder: Yale Institute for Biospheric Studies;Amount awarded: $200,000; Period of performance: 2024-2026; Title: The Role of Deep Roots in Drought-Induced Mortality of Amazonian Tree Species

Funder: Fund for Climate Solutions; Amount awarded: $89,000; Period of performance: 2023-2024; Title: The Importance of Protected Areas and Indigenous Lands for Amazon Climate

TEACHING:

- ENV 610 (graduate), Managing Ecosystems for Climate Change Solutions

Dr. Matthew Eisaman

CURRENT RESEARCH FOCUS
Marine Carbon Dioxide Removal (mCDR)

WEBSITE: https://www.eisamanlab.com/

LAB GROUP:
1 Postdoctoral Researcher; 2 PhD Students; 2 Research Associates; 1 Undergraduate Researcher

SELECTED PUBLICATIONS:

- M.D. Eisaman, Front. Clim., 6, (2024) Pathways for marine carbon dioxide removal using electrochemical acid-base generation. https://doi.org/10.3389/fclim.2024.1349604
- M.C. Ringham, N. Hirtle, C. Shaw, X. Lu, J. Herndon, B.R. Carter, and M.D. Eisaman, EGUsphere (2024) A comprehensive assessment of electrochemical ocean alkalinity enhancement in seawater: kinetics, efficiency, and precipitation thresholds. https://bg.copernicus.org/articles/21/3551/2024/
- M. D. Eisaman et al. (2023) Chapter 3: Assessing the Technical Aspects of Ocean Alkalinity Enhancement Approaches. Guide to Best Practices in Ocean Alkalinity Enhancement Research, edited by: A. Oschlies, et al., Copernicus Publications, State Planet, 2-oae2023, 3 https://doi.org/10.5194/sp-2-oae2023-3-2023
- H. Wang, D. J. Pilcher, K. A. Kearney, J. N. Cross, O. M. Shugart, M. D. Eisaman, and B. R. Carter (2023) Simulated Impact of Ocean Alkalinity Enhancement on Atmospheric CO_2 Removal in the Bering Sea. Earth's Future, 11, e2022EF002816, DOI: 10.1029/2022EF002816

APPENDIX B

YCNCC-ENDOWED FACULTY

SELECTED OUTREACH:

- mCDR via Electrochemical Ocean Alkalinity Enhancement – Invited speaker, Mechanical Engineering Dept Seminar Series, Univ. of Michigan, Ann Arbor, MI, October 2023
- Ebb Carbon's Ocean Alkalinity Enhancement Approach and Development – Plan Sea Podcast: Ocean Interventions to Address Climate Change, November 2023
- Climate Solutions and Ocean Carbon Capture: A Conversation with Dr. Matthew Eisaman – YCNCC Corporate Partner Webinar, November 2023
- Press Conference Participant for The EASE-OA (Electrochemical Acid Sequestration to Ease Ocean Acidification) Project
- Invited panelist, 2023 American Geophysical Union (AGU) Fall Meeting, San Francisco, CA, December 2023.
- Organized YCNCC Spring 2024 Symposium and preceding MRV Workshop on Marine Carbon Dioxide Removal.
- Yale For Humanity Illuminated: New Frontiers in Climate Science: Innovative Solutions For a Sustainable Future, Carbon Dioxide Removal Using the Oceans – Invited speaker and panelist, West Palm Beach, FL, February 2024.

GRANTS:

Funder: US Department of Energy; Amount awarded: $4,999,998; Period of performance: 10/15/23 - 10/14/26; Title: CDR and High-Performance Computing: Planetary Boundaries of Earth Shots

Funder: National Science Foundation; Amount awarded: $1,499,984; Period of performance: 9/1/24 - 8/31/27; Title: ReDDDoT Phase 2: Developing the Principles, Methodologies, and Tools for the Responsible Deployment of Marine Carbon Dioxide Removal

Funder: Grantham Foundation; Amount awarded: $150,000; Period of performance: 9/1/22 - 2/28/25; Title: Acid Pretreatment to Enable Gigaton-Scale CO2 Mineralization in Basalt

TEACHING:

- Fall: EPS 720 (graduate), The Role of the Oceans in Climate Solutions: Physical, Environmental, Societal and Legal Constraints
- Spring: EPS 102 (undergraduate): Understanding Climate Change Solutions

APPENDIX B

YCNCC-ENDOWED FACULTY

Dr. Sparkle Malone

CURRENT RESEARCH FOCUS

Ecosystem and Disturbance Ecology, Methane Dynamics, Blue Carbon

WEBSITE: https://www.malonelab.org/

LAB GROUP:

1 Postdoctoral Researcher; 1 PhD Student; 1 Masters Student; 1 Research Associate

SELECTED PUBLICATIONS:

- Hu T, Malone SL, Rumpel C, Chabbi A (2024) Maximizing soil organic carbon stocks through optimal ploughing and renewal strategies in (Ley) grassland. Nature Communications Earth & Environment, 5(1):1–10. https://doi.org/10.1038/s43247-024-01202-3
- Richardson JL, Desai AR, Thom J, Lindgren K, Laudon H, Peichl M, Nilsson M, Campeau A, Järveoja J, Hawman P, Mishra DR, Smith D, D'Acunha B, Knox SH, Ng D, Johnson MS, Blackstock J, Malone SL, Oberbauer SF, Detto M, Wickland KP, Forbrich I, Weston N, Hung JKY, Edgar C, Euskirchen ES, Bret-Harte S, Dobkowski J, Kling G, Kane ES, Badiou P, Bogard M, Bohrer G, O'Halloran T, Ritson J, Arias-Ortiz A, Baldocchi D, Oikawa P, Shahan J, Matsumura M (2023) On the Relationship Between Aquatic CO2 Concentration and Ecosystem Fluxes in Some of the World's Key Wetland Types. Wetlands, 44(1):1. https://doi.org/10.1007/s13157-023-01751-x
- Poulter B, Adams-Metayer FM, Amaral C, Barenblitt A, Campbell A, Charles SP, Roman-Cuesta RM, D'Ascanio R, Delaria ER, Doughty C, Fatoyinbo T, Gewirtzman J, Hanisco TF, Hull M, Randy Kawa S, Hannun R, Lagomasino D, Lait L, Malone SL, Newman PA, Raymond P, Rosentreter JA, Thomas N, Vaughn D, Wolfe GM, Xiong L, Ying Q, Zhang Z (2023) Multi-scale observations of mangrove blue carbon ecosystem fluxes: The NASA Carbon Monitoring System BlueFlux field campaign. Environmental research letters: ERL, 18(7):075009. https://doi.org/10.1088/1748-9326/acdae6
- Dubos N, Fieldsend TW, Roesch MA, Augros S, Besnard A, Choeur A, Ineich I, Krysko K, Leroy B, Malone SL, Probst J-M, Raxworthy C, Crottini A (2023) Choice of climate data influences predictions for current and future global invasion risks for two Phelsuma geckos. Biological invasions, https://doi.org/10.1007/s10530-023-03082-8

SELECTED OUTREACH:

- Gaps in Network Infrastructure Limit our Understanding of Biogenic Methane Emissions Across the United States – Invited speaker, Ecological Society of America, Portland OR. August 6-11 2023
- Gaps in Network Infrastructure Limit our Understanding of Biogenic Methane Emissions Across the United States – Invited speaker, Blue Flux Team Meeting, Washington DC. September 12-14 2023
- The Path to Effective Methane Emission Management: Insights for Climate Action and Sustainability – Invited speaker, Harvard Forest, Gardner, MA. October 4-6 2023
- EcoCareer Compass – Invited participant, Florida International University Institute of Environment REU, Miami, FL. July 12, 2024
- Disturbance Ecology Lab – Invited participant, Harvard Forest REU, Petersham, MA. July 18, 2024

APPENDIX B

YCNCC-ENDOWED FACULTY

GRANTS:

Funder: The National Science Foundation; Amount awarded: $4,750,800; Period of performance: 2020-2024; Title: LTER: Coastal Oligotrophic Ecosystem Research

Funder: The National Science Foundation; Amount awarded: $2,610,307
Period of performance: 2021-2025; Title: MRI: Development of an Instrument for Student and Faculty Research on Multimodal Environmental Observations

Funder: The National Science Foundation; Amount awarded: $1,137,895; Period of performance: 2021-2026; Title: CAREER: Understanding Coastal Resilience: Implications of an Expanding White Zone in the Florida Everglades

Funder: National Center for Ecological Analysis & Synthesis (NCEAS); Amount awarded: $109,000
Period of performance: 2023; Title: The Flux Gradient Project: Understanding the Methane Sink-Source Capacity of Natural Ecosystems

TEACHING:

- ENV 730a Environmental Data Science in R: Introduction to Data Integration and Machine Learning
- ENV 623 The Role of Methane in Global Climate Disruption: The Search for Solutions

Dr. Eric Slessarev

CURRENT RESEARCH FOCUS
Role of Soil in Terrestrial Ecosystems, Soil-based Climate Change Mitigation Strategies

WEBSITE: https://ericslessarev.com/

LAB GROUP: 3 Postdoctoral Researchers (including 1 YCNCC fellow), 1 Postgraduate Appointee

SELECTED PUBLICATIONS:

- Sokol, N.W., Sohng, J., Moreland, K., Slessarev, E.W., et al. Reduced accrual of mineral-associated organic matter after two years of enhanced rock weathering in cropland soils, though no net losses of soil organic carbon. *Biogeochemistry* (2024). https://doi.org/10.1007/s10533-024-01160-0
- Georgiou, K., Koven, C.D., Wieder, W.R., Hartman, M.D., Riley, W.J., Pett-Ridge, J., Bouskill, N.J., Abramoff, R.Z., Slessarev, E.W., Ahlström, A., Parton, W.J., Pellegrini, A.F.A., Pierson, D., Sulman, B.N., Zhu, Q., Jackson, R.B., (2024). Emergent temperature sensitivity of soil organic carbon driven by mineral associations. *Nature Geoscience* 17, 205–212. https://doi.org/10.1038/s41561-024-01384-7
- Sokol, N.W., Foley, M.M., Blazewicz, S.J., Bhattacharyya, A., DiDonato, N., Estera-Molina, K., Firestone, M., Greenlon, A., Hungate, B.A., Kimbrel, J., Liquet, J., Lafler, M., Marple, M., Nico, P.S., Paša-Tolić, L., Slessarev, E. W., Pett-Ridge, J., (2024). The path from root input to mineral-associated soil carbon is dictated by habitat-specific microbial traits and soil moisture. *Soil Biol. and Biochem.*, 193, 109367. https://doi.org/10.1016/j.soilbio.2024.109367
- Slessarev, E. W., Mayer, A., Kelly, C., Georgiou, K., Pett-Ridge, J., & Nuccio, E. E. (2023). Initial soil organic carbon stocks govern changes in soil carbon: Reality or artifact? *Global Change Biology*, gcb.16491. https://doi.org/10.1111/gcb.16491

APPENDIX B

YCNCC-ENDOWED FACULTY

SELECTED OUTREACH:

- Global Geochemical Thresholds and the Boundaries of Soil Fertility – Invited speaker, University of Maryland Colloquium, January 26, 2024
- University of Maryland Geology Colloquium – Invited participant, February 16, 2024
- UC Riverside Environmental Sciences Departmental Seminar – Invited speaker, March 13, 2024
- National Public Radio: Plant-Based Restaurants are Adding Beef. Does the Climate Math Add Up? – Interview participant, May 19, 2024

GRANTS:

Funder: Lawrence Livermore National Laboratory; Amount awarded: $739,417; Period of performance: 7/17/24 - 9/30/26; Title: Farming Carbon Strategic Initiative (subaward to Yale)

Funder: US DOE, Environmental System Science Division; Amount awarded: $399,255; Period of performance: 9/1/23 - 8/31/24; Title: Understanding the Geochemical Basis for Soil Organic Matter Storage at the Global Scale

TEACHING:

- EEB 639: Soil in the Carbon Cycle
- EEB 762: Ecology of Landforms

APPENDIX C

POSTDOCTORAL FELLOWS

DETAILED FY24 UPDATES

Postdoctoral Fellowship Program:
Attracting and supporting early career researchers that bring novel ideas and perspectives to Yale and the Center is a key mechanism for enabling innovative and cutting-edge science for solving the climate crisis. YCNCC has awarded two new fellowships during the second recruitment round, and those fellowship recipients will be joining the two current YCNCC postdoctoral fellows in Fall 2024. Their projects will expand the research portfolio of the Center and address topics that have the potential to significantly contribute to informed climate solutions.

Dr. Shangshi Liu

FACULTY ADVISOR:
Dr. Mark Bradford, Professor of Soils and Ecosystem Ecology

DEPARTMENT/SCHOOL:
School of the Environment

FOCUS AREA:
Ecosystem Capture

PLANNED RESEARCH PROJECT:
Regenerative Agriculture for Rebuilding Soil Organic Carbon Stock

WHAT IS THE PROJECT ABOUT?

Shangshi Liu's project will explore regenerative agricultural practices, such as crop rotations and managed grazing, and deliver a more transparent, evidence-based picture of the extent to which the adoption of these practices translates to beneficial climate mitigation and adaptation goals. Specifically, Shagshi will:

1) Develop technologies to accurately measure soil organic carbon pools and understand how they respond to soil conditions and management practices
2) Create and assess detailed maps showing changes in soil organic carbon under regenerative agriculture practices to understand their climate mitigation and adaptation benefits.

HOW DOES IT EXPAND THE CENTER'S RESEARCH AGENDA AND RELATE TO EXISTING CENTER RESEARCH:

This fellowship advances YCNCC's mission to foster research on carbon capture that contributes to the implementation of climate solutions. The insights generated by this research specific to soil organic carbon formation and persistence will greatly benefit related projects that the Center is undertaking.

Rebuilding soil organic carbon (SOC) in agricultural soil through regenerative practices is a crucial yet uncertain natural carbon capture solution. This project aims to address the lack of empirical data at the necessary scales of cropland management to evaluate SOC's effectiveness as a climate solution for mitigation and adaptation. It will provide evidence to support the implementation of regenerative agriculture-based carbon capture projects.

APPENDIX C
POSTDOCTORAL FELLOWS

Dr. Fan Yang

FACULTY ADVISOR:
Dr. Yuan Yao, Associate Professor of Industrial Ecology and Sustainable Systems

DEPARTMENT/SCHOOL:
School of the Environment

FOCUS AREA:
Industrial Decarbonization

PLANNED RESEARCH PROJECT:
Decarbonizing the Aviation Sector by Carbon Capture and Utilization

WHAT IS THE PROJECT ABOUT?

Fan Yang's project will explore the potential impact of carbon capture, utilization, and storage (CCUS) in alternative aviation fuels in the context of climate change mitigation over time. This project seeks to answer three main questions:

1) What are the climate change mitigation potential and other environmental impacts of CCUS combined with different sustainable aviation fuel (SAF) production pathways?
2) What is the techno-economic performance of different combinations of CCUS and SAF production systems, and how can the synergies from both environmental and economic impacts be optimized?
3) What are economically feasible pathways to decarbonize the aviation sector in the United States, considering the spatial distribution of natural resources, CO2 point sources, and CO2 storage sites?

HOW DOES IT EXPAND THE CENTER'S RESEARCH AGENDA AND RELATE TO EXISTING CENTER RESEARCH:

In 2019, the aviation sector contributed three percent of the world's greenhouse gas emissions (GHG), with over 400 billion liters of fossil fuel consumed. Further, worldwide passenger miles are projected to double by 2050, relative to 2010. The International Air Transport Association (IATA) has set an industry target to achieve carbon-neutral growth since 2021 and to strive for a 50% emission reduction by 2050 based on 2005 levels. However, it is almost impossible to close the carbon emission gap between the projected and targeted GHG emissions solely by incremental improvement of current fossil-based technologies, air traffic management, and infrastructure. It is urgent to explore alternative feedstocks and disruptive technologies for fuel production and GHG mitigation.

APPENDIX C
POSTDOCTORAL FELLOWS

Dr. Spencer Moller

FACULTY ADVISOR:
Dr. Ruth Blake, Professor of Earth & Planetary Sciences

DEPARTMENT/SCHOOL:
Earth and Planetary Sciences Department

FOCUS AREA:
Enhanced Rock Weathering

PLANNED RESEARCH PROJECT:
Phosphate Oxygen Isotopes: A Proxy to Link Carbon Capture and Biogeochemical Cycling of Phosphorus in Agricultural Soils

WHAT IS THE PROJECT ABOUT?

Spencer's project will explore how the application of basalt rock to croplands for the purpose of carbon sequestration may also reduce the need for certain fertilizers, the use of which can negate or reverse the carbon sequestration potential of certain agricultural practices.

HOW DOES IT EXPAND THE CENTER'S RESEARCH AGENDA AND RELATE TO EXISTING CENTER RESEARCH:

Agricultural management practices were the source of 11% of U.S. greenhouse gas emissions in 2020. While emission reduction opportunities and sink enhancements to sequester carbon from the atmosphere have been implemented into modern land management practices, these are often diminished by excessive applications of fertilizers and manure that contribute to a net carbon positive contribution to the environment. Thus, the future of sustainable management practices for croplands will rely heavily upon the development of novel techniques that offer co-benefits to increase carbon storage as well as mitigate the application rates of fertilizers. This research will also enhance and complement ongoing projects being undertaken by YCNCC researchers, especially those focused on ERW.

APPENDIX C
POSTDOCTORAL FELLOWS

Dr. Mariela Garcia Arredondo

FACULTY ADVISOR:
Dr. Eric Slessarev

DEPARTMENT/SCHOOL:
Ecology and Evolutionary Biology Department

FOCUS AREA:
Ecosystem Capture

PLANNED RESEARCH PROJECT:
Linking Soil Carbon and the Calcium Cycle in Grassland Ecosystems

WHAT IS THE PROJECT ABOUT?

Mariela's project will investigate the interplay between calcium and carbon cycling in grassland ecosystems and evaluate the climate impacts of converting land to agriculture. The research aims to inform nature-based climate solutions targeting grasslands and croplands by developing a mechanistic model that simulates the formation and dissociation of Ca-organic matter (OM) complexes. Laboratory experiments will be conducted on soils from both native grasslands and areas converted to agriculture to parameterize the model. This model will be used to simulate field soil carbon dynamics, highlighting the differences between natural grasslands and agriculturally transformed areas.

HOW DOES IT EXPAND THE CENTER'S RESEARCH AGENDA AND RELATE TO EXISTING CENTER RESEARCH:

This research will address gaps in the understanding of how calcium helps stabilize organic carbon in soils. Specifically, the research will assess the role of soil pH and carbon quality in this process, given evidence that both variables change with management, affecting soil carbon storage. These measurements are crucial because current biogeochemical models, used to evaluate and credit CO_2 drawdown in grassland and cropland systems, do not incorporate the role of Ca as a carbon-stabilizing mechanism.

This project will establish the theoretical framework necessary for linking ERW and lime application to soil carbon cycling, laying the foundation for better life-cycle assessments of these approaches at large spatial scales. More broadly, this research will enhance an understanding of how changes in land use may influence biogeochemical cycles, crucial for aligning CO_2 removal, soil health, and land management with the goal of maintaining a sustainable global food production model.

APPENDIX D
INFRASTRUCTURE UPDATES

Marine Station

YCNCC, in collaboration with the Peabody Museum, is working with University planners to develop a marine sciences station on the Connecticut shoreline. A coastal marine station is vital for mesocosm and field trials for ocean alkalinity enhancement, sea water access and testing, and research on coastal marine ecosystems. A new Yale marine station will serve multiple research and teaching needs for YCNCC scientists, and will add to the network of New England marine stations that all play an important role in climate mitigation as well as advancing our understanding of the effect of climate on marine ecosystems, biodiversity and fishing. Currently two properties in Guilford, CT are under consideration for development: one is an already established science facility in the Guilford Marina. The other is a Yale shore-line property managed by the Museum. Plans, along with technical needs, architectural specifications, and water and ground surveys are being carried out by Yale facilities in collaboration with YCNCC and Museum scientists and leadership.

Osborn Memorial Laboratories

YCNCC will be getting custom-designed space in Osborn Memorial Laboratories (OML), which is currently scheduled for a complete renovation starting in 2025. This permanent YCNCC space will include administrative offices, office space for postdoctoral researchers and visiting scientists, a conference room and kitchen area. The space will be located adjacent to research labs and offices associated with the School of the Environment, the Ecology and Evolutionary Biology Department, and the Yale Institute for Biospheric Studies, fostering interactions between researchers working on natural carbon capture and related fields. YCNCC directors have been meeting regularly with Yale facilities and with architects from HGA, a national interdisciplinary design firm rooted in architecture and engineering that was selected to lead the OML renovation planning.

Osborn Memorial Laboratories

Photo provided by Yale Urban Media Project

APPENDIX E

UPDATES FROM YCNCC-CONNECTED STARTUPS

CREW Carbon

CREW Carbon was co-founded by Dr. Joachim Katchinoff (PhD 2022) and YCNCC Scientific Leadership Team member Dr. Noah Planavsky. The company has developed technology that utilizes engineered enhanced weathering (EW) for permanent and verifiable CO_2 removal in wastewater systems.

KEY FY24 MILESTONES INCLUDE:

- Raised $5.3M in equity funding in an oversubscribed seed round
- Named as one of 24 semifinalists for the U.S. Department of Energy (DOE) CDR Pilot Purchase Prize
- Highlighted as "Innovator of the Month" for June 2024 by the U.S. Senator from Connecticut, Chris Murphy

Ebb Carbon

Ebb Carbon was co-founded by YCNCC Scientific Leadership Team member Dr. Matthew Eisaman. Based on Dr. Eisaman's pioneering research, the company has created a system for storing atmospheric carbon dioxide in seawater while reducing ocean acidity.

KEY FY24 MILESTONES INCLUDE:

- Awarded $1.9M from the National Oceanic and Atmospheric Administration (NOAA) for monitoring, reporting, and verification (MRV) research at the company's first-of-a-kind demonstration deployment at the Pacific Northwest National Laboratory (PNNL)
- Named as one of 20 finalists for the $100M XPRIZE Carbon Removal competition
- Named as one of 24 semifinalists for the U.S. DOE CDR Pilot Purchase Prize

Lithos Carbon

Lithos Carbon was co-founded by YCNCC Scientific Leadership Team member Dr. Noah Planavsky. The company accelerates the Earth's natural carbon cycle by deploying EW in agriculture to permanently remove CO_2 from the air and improve crop yields and soil health for farmers. Lithos uses organic-grade volcanic basalt dust and state-of-the-art science to measure CO_2 removal.

KEY FY24 MILESTONES INCLUDE:

- Secured the world's first offtake purchase agreement for CDR credits from enhanced weathering in the amount of $57.1M from the Frontier Fund
- Named as one of 20 finalists for the $100M XPRIZE Carbon Removal competition
- Named as one of 24 semifinalists for the U.S. DOE CDR Pilot Purchase Prize

APPENDIX E

UPDATES FROM YCNCC-CONNECTED STARTUPS

Mati Carbon

Mati Carbon removes carbon from the atmosphere through the use of basalt-based EW in rice farms, while adding key nutrients to the soil. YCNCC Scientific Leadership Team member Dr. Noah Planavsky co-invented Mati's isotope dilution technology and is a scientific advisor for the company.

KEY FY24 MILESTONES INCLUDE:

- Secured pre-purchase agreements for initial CDR credits from Frontier and Milkywire funds
- Named as one of 20 finalists for the $100M XPRIZE Carbon Removal competition
- Named as one of 24 semifinalists for the U.S. DOE CDR Pilot Purchase Prize

Oxylus Energy

Oxylus Energy was founded in June 2023 based on research sponsored in part by YCNCC from Faculty Affiliate Dr. Hailiang Wang, who serves as the company's Scientific Advisor. The company is developing a highly efficient and scalable electrolyzer technology to transform CO_2 over a proprietary catalyst and electrode to create green chemicals, including e-methanol that can serve as a replacement of traditional fossil fuels supporting a wide array of use cases.

KEY FY24 MILESTONES INCLUDE:

- Company formation in June 2023
- Named as semifinalist for the MIT Climate & Energy Prize
- Raised $4.5M seed funding round

Blue Shift Carbon

Blue Shift Carbon was co-founded by incoming YCNCC Scientific Leadership Team member Dr. David Kwabi and incorporated in July 2024. The company's objective is to enable cost-effective carbon removal from seawater using an electrochemical process involving textile-based electrodes.

APPENDIX F

YCNCC WORKSHOP PROGRAM

Observation Infrastructure for Natural Methane Emissions
September 5-7, 2023

NUMBER OF PARTICIPANTS:

40; (from universities, non-profits, and government)

SUMMARY:

Methane is a potent greenhouse gas that is 34 times more effective at trapping heat than CO_2. Recent increases in atmospheric methane are likely due to natural sources and processes, which are poorly understood and highly uncertain, leaving many questions about what drives methane emissions and how to measure them over time.

This three-day workshop included research and network presentations in addition to breakout sessions focused on assessing research needs. Focus areas included understanding the sources of increased natural methane emissions, determining the types of data and frameworks needed to reduce uncertainty, identifying physical infrastructure needed to advance research priorities, enhancing the accessibility of related data, and devising pathways for continued engagement with the research community. Out of this meeting, participants outlined three papers that address these key issues and advance research into this critical contributor to climate change.

Carbon and Coffee Workshop: The Role of Tropical Crops in Natural Carbon Capture
September 6-8, 2023

NUMBER OF PARTICIPANTS:

59; (from universities, non-profits, and industry)

SUMMARY:

As one of the major food commodities in the world spanning 27 million acres, coffee crops hold tremendous potential for carbon capture and storage. The industry is also incredibly sensitive to the impacts of climate change, as are the 25 million producers and their families who rely on the crop for their livelihoods.

This three-day workshop brought together stakeholders of diverse backgrounds, such as industry professionals, research scholars, smallholder producers, and other leaders working with coffee in the Global South, to explore models of coffee production and trade that can contribute to natural carbon capture; analyze the technical aspects of mapping, measuring, valuing, and trading sequestered carbon produced by the coffee industry; evaluate the impact of new regulations to reduce deforestation and carbon emissions; and enable conditions to realize the potential of carbon capture across coffee production.

APPENDIX F

YCNCC WORKSHOP PROGRAM

The Pressing Need for Incorporating Belowground Processes in Tropical Forest Restoration

November 3-5, 2023

NUMBER OF PARTICIPANTS:

31; (from universities and non-profits)

SUMMARY:

To effectively combat climate change, restoring tropical forests is crucial. However, these restoration strategies often lead to mixed results and failures since success is typically measured by aboveground growth and survival, ignoring important belowground factors like soil nutrients and microbial composition, which have a large impact on total carbon storage, ecosystem function, and biodiversity. Understanding how different restoration strategies can impact belowground dynamics can lead to better and more effective restoration efforts, as well as help local communities adapt to and mitigate the impacts of climate change.

This three-day workshop gathered a diverse group of external and internal academic experts to explore the connections between above and belowground processes in tropical forest restoration efforts and to develop a standardized framework for these efforts. This output will provide crucial guidance for restoration practitioners and lead to more effective restoration interventions going forward.

Tropical Soil Fertility and Forest Dynamics Workshop

February 5-9, 2024

NUMBER OF PARTICIPANTS:

51; (from universities, non-profits, and government)

SUMMARY:

Tropical forests offer large potential for natural carbon capture at a relatively low cost, which has spurred the development of a large number of management and restoration efforts. While the potential is significant, it is not yet clear that increasing forest productivity will necessarily result in increased carbon storage because of a fascinating, yet poorly understood phenomenon: as forest productivity and carbon accrual rates increase, so do rates of tree death and carbon loss.

This two-and-a-half day workshop, brought together leading tropical forest researchers with expertise in different subregions to present their perspectives on the challenges and opportunities and to identify ways to advance the understanding of tropical soils and forest dynamics. The workshop produced a number of outputs, including four peer-reviewed publications and two grant proposals.

APPENDIX F

YCNCC WORKSHOP PROGRAM

Tropical Forest Fires: An Integrated View to Avoid the Tipping Point

March 26-28, 2024

NUMBER OF PARTICIPANTS:

33; (from universities, non-profits, and government)

SUMMARY:

Tropical forests store massive amounts of carbon, but this capacity has recently decreased due to climatic extremes, fires, regional drying, and human-induced forest degradation. In the Amazon, for example, there is a fierce debate about when and if the ecosystem will reach a "tipping point," which could result in a significant loss of biodiversity and the release of large amounts of stored carbon into the atmosphere, exacerbating global climate change. Given the critical importance of this issue and the existing uncertainties, there is an urgent need for a comprehensive understanding of what is known and unknown about this topic and its implications for tropical rainforests around the world.

This three-day workshop provided a forum for dialogue and interaction among scientists, policymakers, and practitioners to help build a road map for the Amazon and other tropical forests. Participants discussed the state of the science, delineated potential thresholds leading to tropical forest instability, and identified policy levers for enhancing forest integrity. Participants addressed these issues and proposed a pathway for moving forward that evaluates potential solutions for increasing the resilience of tropical forests and their populations to major climatic shocks.

Toward an R&D Roadmap to Quantify and Reduce Uncertainty in MRV for Abiotic mCDR

April 24-25, 2024

NUMBER OF PARTICIPANTS:

49; (from universities, non-profits, government, and industry)

SUMMARY:

Marine carbon dioxide removal (mCDR) represents a promising approach to removing large amounts of CO_2 from the atmosphere. Since this strategy works by enabling the ocean to store CO_2 as carbonate ions within seawater, accurately measuring the amount of carbon removal is fundamental, especially as the industry matures and becomes more regulated in the coming years. Reducing uncertainty in mCDR is also crucial for attracting investment and scaling up efforts that can have a significant climate impact.

This two-day workshop brought together stakeholders across academia, industry, and government to develop a research and development roadmap to quickly reduce the uncertainty in monitoring, reporting, and verification (MRV) for mCDR approaches. Participants explored the current state of practices and concepts, major sources and magnitude of uncertainty, and how to apply research and tools to reduce them. The goal of the workshop was to develop standard, practical approaches that the industry can use as it scales.

APPENDIX G

OUTREACH AND ENGAGEMENT

Corporate Engagement:

October 24, 2023
YCNCC Fall Corporate Roundtable meeting took place via Zoom with 30 attendees, including YCNCC faculty members.

November 16, 2023
Corporate educational webinar on marine carbon dioxide removal (mCDR) featuring Dr. Matt Eisaman, which attracted 80 attendees from various companies.

March 17, 2024
Corporate educational webinar featuring Dr. Tony Leiserowitz, Director of the Yale Program on Climate Change Communications, which drew 100 attendees from various companies.

June 5, 2024
Webinar for corporate prospects of the "MRV Initiative", with 19 corporate guests and YCNCC faculty members presenting on their research in this area.

General Outreach and Engagement by YCNCC-Affiliated Faculty and Researchers:

July 2023
- YCNCC-affiliated faculty Dr. Lea Winter conducted lab tour and plasma demonstration for the Yale Pathways Summer Program
- YCNCC-affiliated graduate student Wyatt Arnold gave a presentation titled "Spatial Heterogeneity of Wetland Methane Fluxes" at the Associate of Environmental Engineering Professors National Conference
- YCNCC Scientific Leadership Team member Dr. Nilay Hazari gave a presentation titled "Fundamental Studies of Hydride Transfer Reactions Relevant to Energy Storage" at the Gordon Organometallics Research Conference
- YCNCC-affiliated faculty conducted a workshop focused on the chemistry behind climate change for New Haven School Students

August 2023
- YCNCC Scientific Leadership Team member Dr. Sparkle Malone gave a presentation titled "Gaps in Network Infrastructure Limit our Understanding of Biogenic Methane Emissions Across the United States" at the Ecological Society of America
- YCNCC-affiliated faculty Dr. Hailiang Wang gave a presentation titled "Cobalt Phthalocyanine Catalyzed CO2 Electroreduction to Methanol" at a seminar at Fudan University
- YCNCC-affiliated faculty Dr. Carling Bieg and Dr. David Vasseur gave a presentation titled "The Interactive Nature of Nutrients and Temperature on Population Dynamics" at the Ecological Society of America 2023 Annual Meeting

September 2023
- YCNCC Co-Director David Bercovici gave a lecture titled "Carbon and Climate," which provided an overview of YCNCC's work, at the Energy Sciences Institute
- YCNCC Scientific Leadership Team member Dr. Sparkle Malone gave a presentation titled "Gaps in Network Infrastructure Limit our Understanding of Biogenic Methane Emissions across the United States" at the Blue Flux Team Meeting

APPENDIX G
OUTREACH AND ENGAGEMENT

- YCNCC-affiliated doctoral student Dr. Jacob Peters gave a presentation titled "UAV Remote Sensing Techniques and Challenges for Temperate Forests"
- YCNCC-affiliated faculty Dr. Hailiang Wang gave a presentation titled "Cobalt Phthalocyanine Catalyzed CO2 Electroreduction to Methanol" at the Hong Kong University of Science and Technology
- Yale Forest Forum Fall Speaker Series: Understanding Climate Smart Forestry in Practice
- YCNCC Co-Director Liza Comita presented at the Yale Clean Energy Collaborative Orientation
- YCNCC-affiliated faculty Dr. Carling Bieg gave a presentation titled "Interactions Between Temperature and Nutrients Determine the Population Dynamics of Primary Producers" at the Yale EEB Seminar Series
- YCNCC Scientific Leadership Team member Dr. Sara Kuebbing gave a presentation titled "Carbon and Climate-Smart Forestry: Forest Protection and Management Options for Climate Mitigation" at the Yale Forest Forum
- YCNCC-affiliated faculty Dr. Yuan Yao gave a presentation titled "Life Cycle Systems Modeling for Sustainable Pathways to a Circular Bioeconomy" in the Yale School of the Environment BIOMES seminar series
- YCNCC Scientific Leadership Team member Dr. Noah Planavsky participated in a CDR roundtable briefing for Massachusetts State Senator Michael Barrett.

October 2023

- YCNCC Scientific Leadership Team member Dr. Sparkle Malone gave a presentation titled "The Path to Effective Methane Emission Management: Insights for Climate Action and Sustainability" at Harvard Forest
- YCNCC Scientific Leadership Team member Dr. Matthew Eisaman was an invited speaker at a Mechanical Engineering Department Seminar Series at the University of Michigan
- YCNCC-affiliated postdoctoral researcher Dr. Cole Gross gave a presentation titled "Carbon Storage and Cycling in Cranberry Farm Agroecosystems" at the ASA-CSSA-SSSA International Annual Meeting
- YCNCC-affiliated faculty Dr. Thomas Harris gave a presentation titled "Sequestering Carbon through Protection and Production: Industrial Reforestation in Mata Atlantica, Brazil" at IUFRO
- YCNCC co-hosted a research seminar by Dr. Gretchen Goldman, US Dept of Transportation
- YCNCC Scientific Leadership Team member Dr. Mark Bradford gave a presentation titled "It is Feasible to Quantify the Effect of Agricultural Practices on Soil Carbon Stocks through Sampling" at the ASA-CSSA-SSSA International Annual Meeting
- YCNCC-affiliated faculty Dr. Yuan Yao gave a presentation titled "Systems Analysis for Nature-Based Solutions to Climate Change" at the YCNCC Donor Meeting
- YCNCC-affiliated faculty Dr. Yuan Yao gave a presentation titled "Life Cycle Systems Modeling for Sustainable Circular Bioeconomy" at the University of Toronto & McGill University
- YCNCC-affiliated postdoctoral researcher Dr. Yiming Guo gave a presentation titled "Mesoscale Eddies: The Weather of the Ocean" at the Yale EPS Postdoc Seminar Series

November 2023

- YCNCC Scientific Leadership Team member Dr. Matthew Eisaman was a guest on the Plan Sea Podcast: Ocean Interventions to Address Climate Change
- YCNCC Scientific Leadership Team member Dr. Sara Kuebbing gave a presentation titled "Climate-Smart Forestry in Practice" at the Washington Forest Protection Association Annual Meeting
- YCNCC-affiliated faculty Dr. Hailiang Wang gave a presentation titled "Energy and Environmental Science and Technology Enabled by Molecular Catalysis" at the USERN Congress
- YCNCC-affiliated faculty Dr. Jing Li gave a presentation titled "Significantly Improved Efficiency of CO2/CO Electroreduction to Value-Added Liquid Fuels via Rational Catalyst Design" at the 2023 AIChE Annual Meeting
- YCNCC-affiliated faculty Dr. Lea Winter gave a presentation titled "Oxygenate Production from Plasma-Activated Reaction of CO2 and Ethane at Materials" at the Research Symposium Fall Meeting

APPENDIX G
OUTREACH AND ENGAGEMENT

- YCNCC-affiliated graduate student Yinan Chen gave a presentation titled ""Designing Polymeric Materials and Polymerization Catalysts as Sustainability Solutions"
- YCNCC-affiliated postdoctoral researcher Dr. Adam Yang gave a presentation titled "Ocean-Based CO2 Removal with Enhanced Mineral Weathering: The Effective Settling of Milled Particles from Particle-Laden Flows" at the 76th Annual Meeting of the Division of Fluid Dynamics, American Physical Society
- YCNCC Scientific Leadership Team member Dr. Noah Planavsky participated in a CDR roundtable briefing for Massachusetts State Representative Jeff Roy.

December 2023
- YCNCC Scientific Leadership Team member Dr. Matthew Eisaman participated in the AGU Annual Meeting
- YCNCC-affiliated postdoctoral researcher Dr. Weier Lie gave a presentation titled "Carbon Dioxide Removal by Managing Forests Under Natural Disturbances in the Northeastern US" at the AGU Annual Meeting
- YCNCC-affiliated postdoctoral researcher Dr. Lisa Eash gave a presentation titled "Quantitative Comparison of Soil Organic Carbon Measurement, Reporting, and Verification Protocols in Agricultural Soils" at the AGU Annual Meeting
- YCNCC-affiliated faculty Dr. Edward Bolton gave a presentation titled "Modeling the Response of Enhanced Rock Weathering to Rainfall Pulses" at the AGU Annual Meeting
- YCNCC-affiliated postdoctoral researcher Dr. Laura Toro gave a presentation titled "The Status and Future Benefits of Commercial Tree Plantations in Latin America" at the AGU Annual Meeting
- YCNCC-affiliated faculty Dr. Hailiang Wang gave a lecture titled "Cobalt Phthalocyanine Hybrid Materials: Electrocatalysis for Energy and Environmental Applications" at Tianjin University

January 2024
- YCNCC Scientific Leadership Team members Dr. Sara Kuebbing and Dr. Mark Bradford collaborated with Yale faculty to co-write a public comment about the findings of the Massachusetts Climate Forestry Committee "Forest as Climate Solutions" report
- YCNCC Scientific Leadership Team member Dr. Sara Kuebbing served on the Steering Committee for the 9th American Forest Congress
- YCNCC hosted a "Coffee Hour" for postdoctoral, graduate and undergraduate students
- YCNCC co-hosted a research seminar by Dr. Greeshma Gadikota from Cornell University
- EEB/YCNCC co-hosted a research seminar by Dr. Sharon Billings from the University of Kansas
- YCNCC co-hosted a research seminar by Dr. Justin Bui from the University of California, Berkeley
- YCNCC-affiliated postdoctoral researcher Dr. Kai Lan gave a presentation titled "Developing Multiple-Scale Modeling and Assessment Tools for Fostering Sustainable Bioenergy and Biomaterials" at North Carolina State University
- YCNCC-affiliated postdoctoral researcher Dr. Adam Yang gave a presentation titled "Density Stratified Shear Flows: Ocean Mixing and Carbon Dioxide Removal" at Dalhousie University
- YCNCC-affiliated postdoctoral researcher Dr. Yiming Guo gave a presentation titled "Surface pCO2 Variation Regimes in the Global Ocean" at the Woods Hole Oceanographic Institution Postdoc Symposium

February 2024
- YCNCC Scientific Leadership Team member Dr. Eric Slessarev presented at the University of Maryland Geology Colloquium
- YCNCC-affiliated faculty Dr. Lea Winter was a guest on PodCAT, a podcast for the academic heterogeneous catalysis field
- YCNCC-affiliated faculty Dr. Carling Bieg gave a presentation titled "Ecological Theory for a Changing World: From Equilibrium to Non-Equilibrium Dynamics" at the University of Toronto
- YCNCC Scientific Leadership Team members Dr. Sara Kuebbing and Dr. Matt Eisaman were invited speakers on the panel titled "New Frontiers in Climate Science: Innovative Solutions for a Sustainable Future" at Yale For Humanity Illuminated in Miami, FL

APPENDIX G
OUTREACH AND ENGAGEMENT

- YCNCC Scientific Leadership Team member Dr. Sara Kuebbing co-chaired a one-day scoping dialogue with 30 external participants about the potential for BEF as a climate mitigation strategy
- YCNCC Scientific Leadership Team member Dr. Nilay Hazari gave a presentation to New Haven School Students about chemistry, including concepts related to global warming
- YCNCC-affiliated faculty Dr. Hailiang Wang gave a presentation titled "Cobalt Phthalocyanine Based Hybrid Material Systems for Solar Fuel Production" at the Renewable Energy Solar Fuels Gordon Research Conference
- YCNCC co-hosted a research seminar by Dr. Chae Jeong-Potter from the U.S. National Renewable Energy Laboratory
- YCNCC co-hosted a research seminar by Dr. David Kwabi from the University of Michigan
- YCNCC co-hosted a research seminar by Scientific Leadership Team member Dr. Sara Kuebbing titled "Managing Forests in a Changing World"
- YCNCC co-hosted a research seminar by Dr. Ben Houlton from Cornell University titled "Between a Rock and a Hard Place: Will Enhanced Weathering Bend the Carbon Curve"
- YCNCC-affiliated postdoctoral researcher Dr. Lisa Eash gave a presentation titled "Quantitative Comparison of Soil Organic Carbon Measurement, Reporting, and Verification Protocols in Agricultural Soils" at the Environmental Defense Fund's Agriculture Greenhouse Gas Mitigation Webinar
- YCNCC-affiliated postdoctoral researcher Dr. Adam Yang gave a presentation titled "The Influence of Shear on the Effective Settling of Mineral Particles in the Ocean with Application to Ocean-Based Carbon Dioxide Removal" at the AGU Ocean Sciences Meeting
- YCNCC-affiliated postdoctoral researcher Dr. Yiming Guo gave a presentation titled "Surface pCO2 Variation Regimes in the Global Ocean and the Role of Mesoscale Eddies" at the 2024 AGU Ocean Sciences Meeting

March 2024

- YCNCC Scientific Leadership Team member Dr. Eric Slessarev presented at a seminar hosted by the UC Riverside Environmental Sciences Department
- YCNCC-affiliated faculty Dr. Lea Winter was a guest on a BBC World Service Podcast "The Climate Question"
- YCNCC-affiliated faculty Dr. Carling Bieg gave a presentation titled "Multi-Stressor Responses Across the Ecological Hierarchy: From Equilibrium to Non-Equilibrium Dynamics" at the American Physical Society 2024 March Meeting
- YCNCC Scientific Leadership Team member Dr. Sara Kuebbing gave a presentation titled "Reconciling Competing Forest Carbon Narratives" at The Mature and Old Growth Science Summit: Implementing Climate-Informed Forestry to Foster Resilient Ecosystems
- YCNCC-affiliated faculty Dr. Thomas Harris gave a presentation titled "Carbon Dioxide Removal (CDR) in the Southeast: Tech, Policy & Regional Opportunities" at the University of North Carolina Clean Tech Summit
- YCNCC Scientific Leadership Team member Dr. Sara Kuebbing and postdoctoral researcher Dr. Weier Liu met with the California Air Resources Board (CARB) to present their research from the Roads to Removal Report and discuss methods for assessing forest carbon storage potential
- YCNCC-affiliated master student Yeim We and others gave a presentation titled "The Impact of Eucalyptus Reforestation on Soil Carbon and Nutrients in Former Pastureland within the Atlantic Forest Region of Brazil: A 30-Year Chronosequence Analysis" at the New England Society of American Foresters Annual Meeting
- YCNCC Scientific Leadership Team member Dr. Mary-Louise Timmermans participated in the webinar "Marine Carbon Dioxide Removal (mCDR)" hosted by the Northeast Regional Ocean Council
- Dr. Joe Roman presents presented a YCNCC-hosted seminar titled "Eat, Poop, Die: How Animals Make Our World"
- YCNCC-affiliated postdoctoral researcher Dr. Yiming Guo gave a presentation titled "Best Practices and Challenges of LCA for Forest Products" at the 11th Forestry and Agriculture GHG Modeling Forum & U.S. DOE Office of Fossil Energy and Carbon Management and Bioenergy Technologies Office

APPENDIX G
OUTREACH AND ENGAGEMENT

- YCNCC-affiliated postdoctoral researcher Dr. Adam Yang gave a presentation titled titled "Fluid Mechanics in Marine Carbon Dioxide Removal" at Colorado State University
- YCNCC-affiliated postdoctoral researcher Dr. Yiming Guo gave a presentation titled "The Role of Ocean Mesoscale Variability in Air-Sea CO2 Exchange" at the Woods Hole Oceanographic Institution Physical Oceanography Seminar

April 2024
- YCNCC Co-Director David Bercovici gave a lecture gave to the Yale Emerging Climate Leaders Fellowship
- YCNCC-affiliated faculty Dr. Lea Winter participated in a workshop titled "Mobilizing Our Universities for Education on Energy Use, Carbon Emissions and Climate Change"
- YCNCC-affiliated faculty Dr. Carling Bieg gave a presentation titled "Building an Understanding of Nonequilibrium Dynamics in Ecological Systems" at the McMaster University MathBio Seminar Series
- YCNCC-affiliated masters student Yeim We and others gave a presentation titled "The Impact of Eucalyptus Reforestation on Soil Carbon and Nutrients in Former Pastureland within the Atlantic Forest Region of Brazil: A 30-Year Chronosequence Analysis" at the Yale School of Environment Research Day
- YCNCC-affiliated doctoral student Jacob Peters gave a presentation titled "Comparing the Spatial Distribution of Native and Non-native Lianas Along Urban Edges: A Case Study of a Mid-sized US City" at the Yale School of the Environment Research Day
- YCNCC-affiliated faculty Dr. Alan Rooney and others gave a presentation titled "Quantifying the Role of Fe-oxide Mineral Absorption on the Marine Os-Re Geochemical Cycle"
- YCNCC Spring Symposium (see below for details)
- YCNCC Scientific Leadership Team member Dr. Noah Planavsky hosted the ERW24 symposium
- YCNCC Scientific Leadership Team members Dr. Matt Eisaman and Dr. Noah Planavsky attended the 2024 Carbon to Sea Convening of the ocean alkalinity enhancement research community in Washington D.C.
- YCNCC-affiliated faculty Dr. Edward Bolton gave a presentation titled "The Impact of Secondary Mineral Precipitation Modeling on Carbon Dioxide Removal Rate Estimates for Enhanced Rock Weathering" at ERW24

May 2024
- YCNCC Scientific Leadership Team member Dr. Eric Slessarev was interviewed for an NPR story titled "Plant-based restaurants are adding beef. Does the climate math add up?"
- YCNCC-affiliated faculty Dr. Lea Winter, postdoctoral researcher Julia Simon, and graduate student Ji-Yong Kim gave a presentation titled "Electrochemical Plasma-Activated CO2 Reduction at a Plasma-Water Interface" at the Electrochemical Society Meeting
- YCNCC-affiliated faculty Dr. Lea Winter, postdoctoral researcher Julia Simon, and graduate student Ji-Yong Kim gave a presentation titled "Electrocatalytic Conversion of Plasma-Activated CO2 Toward Multicarbon Products" at the Electrochemical Society Meeting
- YCNCC-affiliated faculty Dr. Carling Bieg and Dr. David Vasseur gave a presentation titled "Variable Habitat Size and Implications for Food Web Dynamics" at the CSEE 2024 Annual Meeting

June 2024
- YCNCC Scientific Leadership Team member Dr. Sparkle Malone presented at the Harvard Forest REU EcoCareer Compass
- YCNCC Co-Director Dr. Liza Comita and YCNCC Scientific Leadership Team member Dr. Paulo Brando gave presentations about Center activities at the Tanguro 20th Anniversary Symposium in Brasilia, Brazil
- YCNCC-affiliated faculty Dr. Anitra Thorhaug gave a talk about Sri Lanka blue carbon mapping as model for blue carbon in the Indian Ocean

APPENDIX G
OUTREACH AND ENGAGEMENT

July 2024

- YCNCC Scientific Leadership Team member Dr. Sparkle Malone presented at the Harvard Forest REU Disturbance Ecology Lab
- YCNCC Scientific Leadership Team member Dr. Sparkle Malone at the Florida International University Institute of Environment REU EcoCareer Compass
- YCNCC-affiliated faculty Dr. Carling Bieg, Dr. Sam Fey, and Dr. David Vasseur gave a presentation titled "Variable Habitat Size and Implications for Food Web Dynamics" at the Gordon Conference for Unifying Ecology Across Scales
- YCNCC Co-Director Dr. Liza Comita gave a lecture on the role of forests in shaping climate to 150 visiting high school students from around the world through the Yale Young Global Scholars Program
- YCNCC Scientific Leadership Team member Dr. Pete Raymond attended an invitation-only White House Super Pollutants Summit at the White House in Washington, D.C.
- YCNCC Scientific Leadership Team member Dr. Jim Saiers attended an invitation-only workshop on Practices and Standards for Plugging Orphaned and Abandoned Hydrocarbon Wells at the National Academy of Sciences, Engineering, and Medicine in Washington, D.C.

Environmental Leadership and Training Initiative (ELTI) –Additional Detail

Summary of Events Completed

- Implemented 13 blended, field, and online courses (not including the ELTI seminar taught for YSE students) that reached 534 participants working in 60+ countries.
- Trained 360 people during 5 online short courses and the yearlong TFL certificate.
- Implemented a four-part webinar series titled "Agroforestry and Carbon: Addressing Climate Change Through Tree-Based Agriculture in Tropical Regions" during this period. A total of 290 people attended at least one of the webinars, which featured YSE alumni, ELTI alumni, and other expert speakers. YSE faculty member, Dr. Florencia Montagnini, provided strategic advice on the design and speaker selection.
- ELTI's Massive Open Online Course (MOOC), hosted on Yale's Coursera platform, continues to grow in popularity. The course, titled "Tropical Forest Landscapes 101: Conservation & Restoration," has over 9,000 learners enrolled from around the globe and boasts a 4.9 out of 5 rating for participant satisfaction. The ELTI team developed this course in collaboration with Yale's Poorvu Center for Teaching & Learning (PCTL) and is planning to develop additional Coursera offerings due to the success of this initial experience.

Summary of Events Completed

- The ELTI team has made significant strides by strengthening partnerships with two existing field programs in Brazil and Indonesia, negotiating a new partnership to host the Panama program, and securing a new partner to launch a field program in Rwanda.
  - Southern Bahia, Brazil: The ELTI team hosted an all-day workshop focused on forest landscape restoration in Southern Bahia, Brazil. The workshop brought together students, faculty, and staff members associated with The Forest School at the Yale School of the Environment to discuss research, teaching, and applied initiatives. Representatives from ELTI's primary partner in Brazil, the Institute for Ecological Research (IPÊ), also attended the meeting to share their work, including their capacity development activities as part of the ELTI project. The workshop generated recommendations for future collaborations, which the ELTI and IPÊ teams will incorporate into their strategy for expanding the ELTI-IPÊ training landscape.
  - East Kalimantan, Indonesia: The ELTI team has been collaborating closely with partner Blue Forests in East Kalimantan, Indonesia, to develop a global online course focused on Blue Carbon. To discuss progress and further advance the curriculum, the ELTI team will host a Blue Carbon Ecosystems Workshop at YSE, funded by YCNCC and the Yale Forests Forum. The

APPENDIX G
OUTREACH AND ENGAGEMENT

expected outcomes include: (1) a peer-reviewed and refined outline of the new online course, "Mangrove Restoration and Blue Carbon," and (2) a strategic plan for advancing the ELTI-Blue Forests training landscape in Indonesia.

- The ELTI team successfully negotiated a new partnership with the Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC) to host the ELTI program in Panama. Beginning in January 2025, CATHALAC will employ ELTI's Panama Coordinator, Jacob Slusser, and administer training and leadership program funds focused on implementing forest restoration courses in cattle ranching landscapes and supporting landholders in sharing and applying the knowledge they have gained. Additionally, the ELTI team hired Coral Keegan (MEM 2023) as a postgraduate associate from January to July 2024 to explore opportunities for launching a new native species restoration initiative in Rwanda. Coral worked closely with Professor Amy Vedder and ELTI Director Eva Garen on this project, which led to an exciting new partnership with the Wildlife Conservation Society. The ELTI team also received a Yale Planetary Solutions seed grant of $120,000 to support the initiative, which is set to launch in September 2024.

Presentations Delivered

- July 9, 2023: CIPAV-ELTI Colombia program coordinator, Zoraida Calle, presented "The Soil: Secrets of a Very Close Stranger" at AgroCultura Caribe, a weekly series on sustainable agriculture broadcast on Facebook Live and YouTube to a Latin American audience. The presentation introduced soil organisms, their relationships with plants, and key biological processes in the rhizosphere that explain soil fertility and nutrient cycling. Calle also discussed how soil functions are impaired by erosion and degradation and how they can be restored through agroecology.
- July 19, 2023: Jacob Slusser presented "Climate Change Resilient Cattle Ranching is Possible and Beneficial for Panama's Rural Economy" at the National Meeting on Sustainable Development (ENADES). This ten-minute presentation described ELTI's efforts and the impact of sustainable cattle ranching capacity development in the Azuero Peninsula, illustrating how silvopastoral systems can adapt to climate change and support the rural economy.
- October 18–19, 2023: Blue Forests-ELTI Indonesia program coordinator, Lely Puspitasari, gave presentations to more than 20 attendees at the Solomon Islands Ranger Association (SIRA) community engagement and high conservation value (HCV) workshop. On the first day, she focused on community engagement through participatory rural appraisals and participatory mapping. On the second day, she covered HCV identification, management, and monitoring.
- February 28, 2024: Jacob Slusser presented "Forest Restoration in Cattle Ranching Landscapes of the Neotropics: Silvopastoral Systems" in Professor Mark Ashton's seminar course for YSE master's students, "Tropical Forest Restoration (ENV 685)." The presentation included a literature review of silvopasture science, a practical explanation of the five silvopastoral system components, and a case study about successful application of silvopasture in Panama.
- March 25, 2024: Slusser presented "Capitalizing on Failures: Lessons Learned Conducting Forest Landscape Restoration With a Community Association in Panama's Azuero Peninsula" in Dr. Eva Garen's seminar course for YSE master's students, "Theory and Practice for Engaging Landholders and Communities in Conserving and Restoring Tropical Forest Landscapes (ENV 685)." The presentation illustrated ELTI's failures, lessons learned, and new approaches to conducting forest landscape restoration with a community association in Panama's Azuero Peninsula.
- April 8, 2024: ELTI's global advisor, David Neidel, gave a presentation titled "Rainforestation for Livelihoods, Biodiversity, and Ecosystem Services" in Professor Ashton's seminar for YSE master's students, "Tropical Forest Restoration (ENV 683b)." The presentation introduced the system of native species reforestation developed in the Philippines to address a variety of management objectives.
- April 22, 2024: Puspitasari and Neidel presented "Incentivizing Community Participation in Mangrove Restoration, East Kalimantan, Indonesia" in Dr. Garen's seminar for YSE master's students, "Engaging Landholders and Communities to Conserve and Restore Tropical Forest Landscapes (ENV 685)." The presentation provided an overview of the approach that ELTI's partner, Blue Forests, takes to addressing livelihood needs as a strategy to engage communities in mangrove restoration.

APPENDIX G
OUTREACH AND ENGAGEMENT

- April 26, 2024: Puspitasari was invited to present at the Blue Carbon Dialogue by CIFOR on February 20, where she discussed Blue Forests' approach to ecological mangrove rehabilitation. After the presentation, CIFOR interviewed Puspitasari to share her experience with Blue Forests and ELTI on mangrove rehabilitation activities. The interview was published by CIFOR on April 26, 2024.

Publicity and Recognition

- ELTI was featured in a web article published by FAO titled "Enhancing the Capacities of Young Forest and Landscape Practitioners in Africa and Asia," which showcased the experiences of two participants from the joint ELTI-FAO online courses on Forest Landscape Restoration conducted in 2023.
- The Forest School (TFS) at Yale highlighted ELTI's Tropical Forest Landscapes (TFL) Certificate Program in an article in their publication The Overstory. The article, "ELTI Trains Fifth Cohort of the Tropical Forest Landscapes Certificate Program," discussed the program's evolution, the current fifth cohort of participants, and the upcoming application cycle.
- TFS also highlighted a workshop organized by ELTI in another Overstory article titled "ELTI Leverages TFS and Partner Collaborations in Brazil." The article covered the workshop, which brought together ELTI staff, YSE faculty, TFS doctoral students, and representatives from The Forests Dialogue with ELTI's Brazilian collaborators from IPÊ and UFSB (Federal University of Southern Bahia). The workshop's goals included learning about each other's work in southern Bahia and sharing ideas for collaboration.
- The YSE Communications Office published an article titled "Accelerating Global Climate Action," featuring Three Cairns scholarship recipients.
- The ELTI team regularly writes short communication stories highlighting how ELTI alumni apply and share the knowledge gained from ELTI courses (see alumni stories featured on the ELTI website). In FY24, the team added three new alumni stories from Indonesia, Panama, and the Philippines:
  - Leading People with Disabilities in Rainforestation Initiatives (Philippines)
  - Exploring Forest Landscape Restoration by Birds (Panama)
  - Supporting Honey Production to Help Conserve Mangrove Forests (Indonesia)

YCNCC 2024 Spring Symposium

Keynote address: mCDR – the view from NOAA, Dr. Sarah Kapnick, Chief Scientist for NOAA

Panel: Monitoring, Reporting, and Verification – Challenges and Opportunities. Dr. Alicia Karspeck, [C]Worthy (moderator); Prof. David Ho, [C]Worthy; Anu Kahn, Carbon180; Anna Madlener, Carbon to Sea Initiative; Dr. Jenny Mills, Cascade Climate.

Isometric's MRV protocol for OAE, Dr. Jennifer Yin, Isometric

Impulse response functions as a framework for quantifying carbon uptake associated with ocean alkalinity enhancement, Dr. Elizabeth Yankovsky, [C]Worthy and Yale University

Mapping the global variation of OAE efficiency for CDR, Mengyang Zhao, University of Connecticut

OAE simulation: Model uncertainties and atmosphere feedback effects, Dr. Michael Tyka, Google

The additionality problem of OAE, Prof. Lennart Bach, University of Tasmania

APPENDIX G
OUTREACH AND ENGAGEMENT

The U.S. Government's Fast Track Action Committee for Marine CDR, Dr. Greg Frost, NOAA

Panel: The State of mCDR Carbon Removal Purchases and Investment. Toby Bryce, The OpenAir Collective (moderator); Katie Sierks, Microsoft; Joanna Klitzke, Stripe; Rory Jacobson, DOE; Dr. Marc von Keitz, The Grantham Foundation for the Protection of the Environment; Reece Pacheco, Propeller VC.

Banyu Carbon: Carbon Removal Powered by Sunlight and Seawater, Prof. Alex Gagnon, Banyu Carbon

The Accelerated Weathering of Limestone on Ships, Prof. Jess Adkins, Calcarea

Accelerating the responsible development of OAE technologies through non-profit science, Dr. Grace Andrews, Hourglass Climate

Emerging sensing and instrumentation technology for MRV in support of mCDR commercialization, Dr. Ellen Briggs, Aquatic Labs

Planetary's OAE Deployment in Nova Scotia: Past, present, and future, Dr. Will Burt, Planetary Technologies

Progress in developing direct ocean capture technology for marine carbon dioxide removal, Dr. Sophie Chu, Captura

Equatic-1: Pioneering the Future of Carbon Removal and CarbonNegative Hydrogen Production at Scale,
Prof. Erika La Plante, Equatic

Developing an Operational Solution for MRV, Prof. Thomas Peacock, atdepth MRV

Laboratory and field MRV development to support OAE pilot trials, Dr. Mallory Ringham, Ebb Carbon

Panel: Responsible deployment of mCDR - Managing the tension between caution and urgency. Dr. Gabby Kitch, NOAA (moderator); Dr. Rudy Kahsar, Rocky Mountain Institute; Dr. Sifang Chen Carbon180; Brad Ack, Ocean Visions; Freya Chay, CarbonPlan

Panel: Policy, regulation, and standards. Hara Wang, Cascade Climate (moderator); Romany Webb, Columbia University; Anu Kahn, Carbon 180.

YCNCC Fall 2023 Research Showcase

YCNCC hosted a Research Showcase in October 2023 that enabled the Yale community to learn more about current research at Yale focused on carbon capture. Attendees were able to network with researchers from multiple departments, centers and schools. This event created a valuable opportunity for students and researchers alike to nurture existing collaborations and create new ones. The one-day event featured a series of 22 lightning talks on subjects in the areas of ecosystem carbon capture; geological and ocean capture; and industrial carbon utilization. Awards were given for Best Undergraduate Student Talk, Best Graduate Student Talk, and Best Postdoc Talk, based on reviews by YCNCC Scientific Leadership Team members. Talks included:

Phosphate Oxygen Isotopes: A Proxy to Link Carbon Capture and Biogeochemical Cycling of Phosphorus in Agricultural Soils,
Dr. Spencer Moller, Postdoctoral Researcher

APPENDIX G
OUTREACH AND ENGAGEMENT

Carbon Dioxide Removal Using the Oceans, Dr. Matthew Eisaman, Associate Professor

Evaluation of Modeling Approaches for Enhanced Weathering, Dr. Edward Bolton, Senior Research Scientist

Mitigating N2O Emissions from Agricultural Corn Settings with Basalt Amendments, Isabella Chiaravalloti, PhD Student

Potential for Enhanced Rock Weathering Deployments: A Geospatial Analysis of Farmlands Across the U.S., Beck Woollen, Postgraduate Associate; Noemma Olagaray, Postbaccalaureate Researcher

Enhanced Rock Weathering Pilot Projects on Agricultural Soils: A Yale-USDA Partnership, Beck Woollen, Postgraduate Associate; Sophie Spiegel, Postgraduate Associate

Assessing the Feasibility of Soil Based Mass Balance Approaches to Quantify CO_2 Removal from Enhanced Rock Weathering for Soils of the Contiguous USA, Dr. Tim Jesper Suhrhoff, Postdoctoral Researcher

Assessing the Effective Settling of Mineral Particles in the Ocean with Application to Ocean- Based Carbon-Dioxide Removal, Dr. Adam Jiankang Yang, Postdoctoral Researcher

Watershed Responses to Enhanced Mineral Weathering: Implications for CO Removal via Natural Water Alkalinization, Dr. Fengchao Sun, Postdoctoral Researcher

Electrochemical Conversion of Pre-Activated CO2 through Plasma towards Chemicals and Fuels, Dr. Ji-Yong Kim, Postdoctoral Researcher

Comparative Studies of CO_2 Insertion into Pincer Supported Pd Alkyl Bonds, Tony Deziel, Graduate Student

Designing Plasma-Electrochemical System for Carbon Upgrading, Julia Simon, Ph.D. Student

The Status and Future Benefits of Commercial Tree Plantations in Latin America, Dr. Laura Toro, Postdoctoral Researcher

The Global Carbon Consequences of Innovative Wood Products, Dr. Yuan Yao, Associate Professor of Industrial Ecology and Sustainable Systems

Integrating Megafauna with Ecosystem Carbon Cycling: Collaborating across Institutions and Disciplines to Explore Moose Management and Boreal Forest, Dr. Elizabeth Forbes, Postdoctoral Researcher

Building Confidence in Agricultural Soil Carbon Credits: Testing the Infeasibility Assumption, Dr. Mark Bradford, Professor of Soils and Ecosystem Ecology

Climate benefits of forest management under threats of natural disturbance in Northeastern United States, Dr. Weier Liu, Postdoctoral Researcher

Sequestering Carbon through Protection and Production: A Case Study of Industrial Reforestation in Mata Atlantica, Brazil, Dr. Thomas Harris, Professor in the Practice Yale Film and Media Studies & African American Studies

APPENDIX G
OUTREACH AND ENGAGEMENT

Mapping Liana Infestation of US Forests using Google Earth Engine, Jacob Peters, Doctoral Student

Assessing Differences in Edge Effects across Planted Forest and Pastureland on Establishment of Secondary Forest in Brazil, Manny Flores, Doctoral Student

Using Radiocarbon (14C) to Improve our Understanding of Blue Carbon Stocks Globally, Dr. Derrick Vaughn, Postdoctoral Researcher

Interactions Between Temperature and Nutrients Determine the Population Dynamics of Primary Producers, Dr. Carling Bieg, Postdoctoral Research