Scientific Research for Natural Solutions to Mitigate Climate Change

Yale *Center for Natural Carbon Capture*

2023 STEWARDSHIP REPORT

A Letter from the Center Directors

To our corporate partners:

It is with great pride that we share this year's annual report for the Yale Center for Natural Carbon Capture. In their 2023 Synthesis Report, the Intergovernmental Panel on Climate Change stated that although current warming projections are set to surpass the critical threshold of 1.5 degrees Celsius in the 21st century, immediate significant and sustained mitigation efforts in this decade could substantially lessen the harm to both humans and ecosystems. The work of the Center contributes significantly to efforts to develop and successfully implement such mitigation efforts at scale.

The Center currently funds four major research initiatives, as well as 17 related research projects. We have succeeded in rapidly engaging scientists at Yale, who have initiated collaborative projects across ecosystems, with broad topics ranging from geological and ocean capture, carbon dioxide utilization, and ecosystem carbon capture. These projects involve students, postdocs, and collaborators from around the world, and include field programs and ongoing experiments in the US, Latin America, Europe, and Asia. This international network consisting of scientific, corporate, NGO, and government partners is imperative to address this global crisis. Our extensive network of research talent has allowed the Center to pursue exciting and groundbreaking research, truly positioning YCNCC as a global leader in climate change solutions.

We are eager to share updates about the Center's research and outreach activities encapsulated in this report. It has been our privilege to discuss these projects with you over the past two years, answer questions, and share in your excitement. We look forward to your feedback and our continued work together to make meaningful progress towards impactful climate solutions.

Sincerely,

David Bercovici and Liza Comita

Co-Directors, Yale Center for Natural Carbon Capture

"At the Center we seek to better understand how natural processes can be enhanced to create reliable and scalable strategies to reduce atmospheric greenhouse gas concentrations while leveraging co-benefits. We do this by supporting innovative research, education, and engagement."

—

From the Yale Center for Natural Carbon Capture Mission Statement

2023 STEWARSDSHIP REPORT 0

Salt marsh; Photo by Pete Raymond

Preface

This second annual stewardship report details the progress in building the Yale Center for Natural Carbon Capture and explains how the cutting-edge research funded by the Center moves the scientific understanding of natural processes for capturing carbon towards generating solutions that will help solve the climate crisis.

One of our major accomplishments this past year is the hiring and on-boarding of four new faculty across three academic units. Their work covers the spectrum of critical areas in natural climate solutions, from forest and soil carbon to methane fluxes to ocean-based carbon capture. Who they are and their research are discussed in detail below. The search for a fifth faculty position in engineering approaches is currently underway.

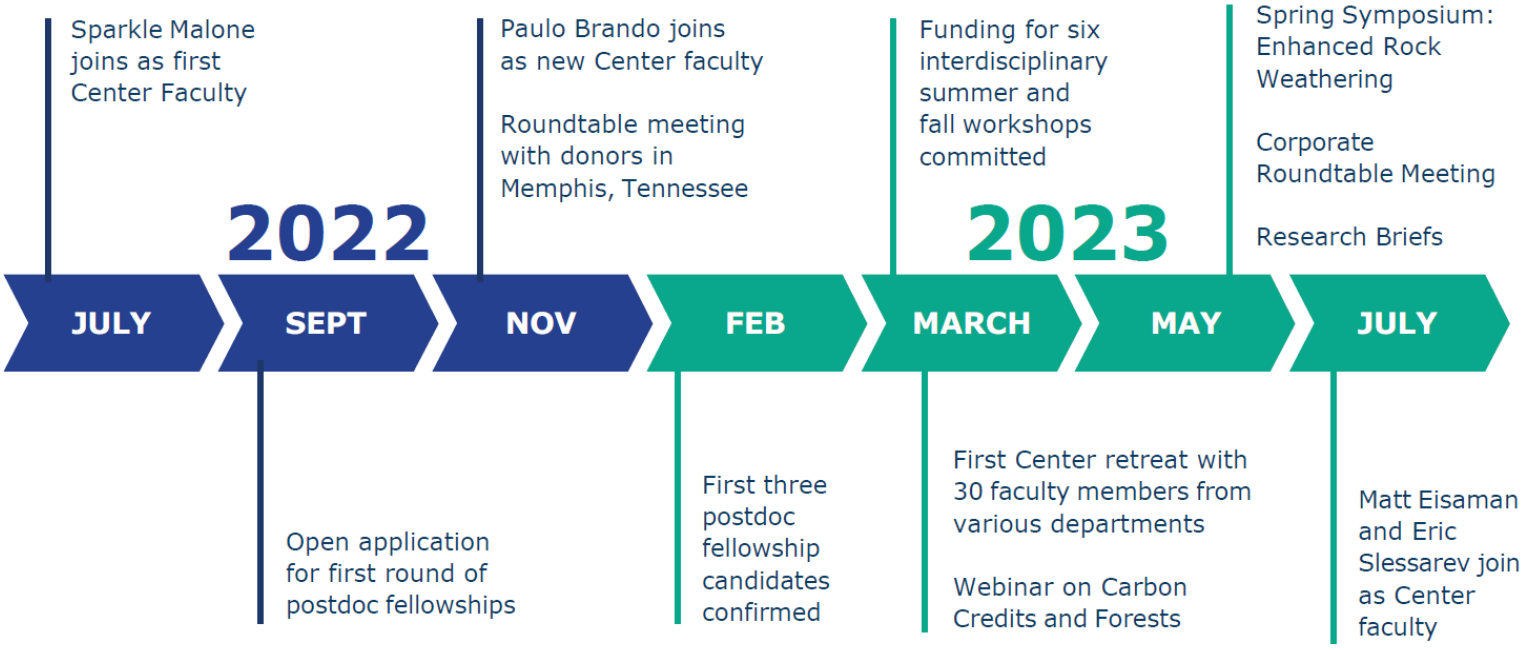
This past year, we have made substantial progress in several key areas. First, through the work of the Yale Applied Science Synthesis Program, one of our major research initiatives, we have worked with decision-makers, practitioners, companies, government agencies, and scientists on all levels to develop guidance for meaningful ecosystem (forest, soil) carbon credit standards that are leading the way to creating a transparent and impactful carbon credit market.

The Center has also emerged as a leader in enhanced rock weathering (ERW) – a proposed climate change mitigation technique that accelerates the natural process of chemical weathering of rocks to capture and store carbon dioxide. The Center has invested in large scale field trials of enhanced rock weathering in agricultural systems. Our work is providing critical measurements needed to quantify the full potential of this climate solution. In addition, the Center brought together leading experts from across the globe and various sectors for a symposium at Yale in May 2023 to discuss and foster collaboration on implementing enhanced rock weathering for carbon capture and durable storage.

This past year we also substantially increased our investment in ocean-based climate solutions, with the hire of Professor Matt Eisaman. Dr. Eisaman, along with his research team, brings expertise in Ocean Alkalinity Enhancement, which has massive capture and storage potential as well as the co-benefits of reducing ocean acidification, such as improved coral reef health.

In this report, we highlight major milestones and provide additional details of the scientific advances made by the Center, including the expansion of scientific expertise and infrastructure in the field and lab. We also report our major outreach and engagement activities, including corporate education, and provide an overview of our evolving communications strategy.

MAJOR MILESTONES



New Faculty Hires

The generous gift from the FedEx Corporation to establish the Yale Center for Natural Carbon Capture included funding for four new endowed faculty positions with which to expand Yale's scientific expertise. In 2022, the Center successfully led and completed a multiple school/department faculty cluster search for all four positions, to rapidly build center expertise and foster opportunities to integrate across disciplines. Two of these positions are housed at the Yale School of the Environment, and two in the Faculty of Arts & Sciences, specifically in the Departments for Earth & Planetary Sciences and Ecology & Evolutionary Biology.

In addition to their unique expertise, each new faculty member brings their own research program with students and postdocs, with new laboratory space and field programs, as well as connections to global networks of leaders in natural carbon capture and nature-based climate solutions.

Matt Eisaman

Associate Professor (with tenure)
Department of Earth & Planetary Sciences

AREA OF EXPERTISE

Professor Eisaman's research has covered a broad range of clean-energy technologies, including photovoltaics and conversion of extracted ocean CO2 to fuels. His current research is focused on carbon dioxide removal (CDR) through ocean alkalinity enhancement, which exploits one of the Earth's largest and fastest CO2 sinks, while also providing the co-benefit of de-acidifying the oceans to improve coral reef health. He has pioneered electrochemical techniques to buffer ocean acidity and enhance the uptake and sequestration of dissolved inorganic carbon which has a 10,000-year storage lifetime.

In 2021, Matt co-founded Ebb Carbon, a startup based in San Carlos, CA that is commercializing ocean-based carbon dioxide removal (ocean CDR) using his method of electrochemical ocean alkalinity enhancement. He currently serves as Ebb Carbon's Chief Scientific Advisor. Professor Eisaman served as a technical advisor to X, formerly known as Google[X], from 2014 - 2021, and in 2016 he led Project Foghorn at X, which aimed to create carbon-neutral liquid fuel from seawater.

TEACHING

Professor Eisaman will teach classes on climate change solutions, carbon dioxide removal, and the history of geoengineering.

MAJOR RESEARCH PROJECTS

- Investigating the optimization and commercialization of electrochemical ocean alkalinity enhancement and atmospheric carbon dioxide removal
- Determining how electrochemical ocean alkalinity enhancement affects marine ecosystems
- Establishing and improving methods for measurement, reporting, and verification (MRV)
- Exploring the potential for colocation and co-benefits of electrochemical ocean carbon dioxide removal with other carbon removal approaches

Paulo Brando

Associate Professor
Yale School of the Environment

AREA OF EXPERTISE

Professor Brando's research focuses on identifying ecological thresholds beyond which global changes cause abrupt, prolonged degradation of terrestrial ecosystems by stressing, disturbing, and killing forests.

He has also studied ecological and climatological boundaries for tropical agricultural expansion and intensification. His research has broadened our understanding of how tropical conservation mitigates climate change and enhances natural carbon capture.

Paulo Brando's research group focuses on finding natural climate solutions through conservation and management of terrestrial ecosystems, with focus in the Amazon and Cerrado Biomes. To advance this science, the group relies on field work, mostly in the Brazilian Amazon, ecological modeling, and the use of remote sensing techniques.

TEACHING

Professor Brando will teach classes on managing ecosystems for climate solutions and tropical sustainable landscapes.

MAJOR RESEARCH PROJECTS

- Investigating how agricultural intensification and climate may alter fire regimes and tropical forest carbon stocks
- Identifying pathways for integrating food production, water use, energy demand, and environmental integrity in a changing climate
- Understanding the current and legacy effects of deforestation and forest degradation on biodiversity, carbon cycling and stocks, and water resources across the Amazon agricultural frontier

Sparkle Malone

Assistant Professor
Yale School of the Environment

AREA OF EXPERTISE

Professor Malone studies carbon dynamics and ecosystem function across space and time, with a focus on methane fluxes, to build natural climate solutions that benefit both nature and people.

One major research theme at the Malone Disturbance Lab is investigating carbon dynamics in coastal wetlands. Coastal wetlands are important natural carbon sinks. These systems are also very sensitive to disturbances such as sea level rise caused by climate change. Understanding the dynamics in coastal wetlands will lead to the development of management practices that can support long term carbon storage in coastal wetlands.

Ultimately, Professor Malone's research efforts seek to develop natural climate solutions that broadly benefit both wildlife and people.

TEACHING

Professor Malone will teach classes on methane dynamics and on methods for investigating and quantifying methane dynamics in natural systems.

MAJOR RESEARCH PROJECTS

- Investigating methane emissions from natural and managed ecosystems to understand sources and sinks to inform future climate change mitigation strategies
- Investigating the effects of increased freshwater inputs and saltwater intrusion on the greenhouse carbon balance of Everglade wetlands
- Determining the role of hurricanes in increasing methane emissions and the global warming potential in Everglades ecosystems
- Exploring how various agricultural practices influence soil carbon sequestration

Eric Slessarev

Assistant Professor
Department of Ecology and Evolutionary Biology

AREA OF EXPERTISE

Professor Slessarev's work focuses on soil and its role in terrestrial ecosystems. His research aims to understand how soil properties develop in different ecological contexts, and how they are expressed at the global scale. Additionally, he investigates how the soil environment governs belowground ecology and influences carbon and nutrient cycling.

Professor Slessarev uses the findings from his fundamental research to evaluate soil-based climate change mitigation strategies and develop and implement new approaches for natural carbon capture in soils across the globe.

TEACHING

Professor Slessarev will teach classes on soils, ecosystems, and soil plant feedback in the global carbon cycle.

MAJOR RESEARCH PROJECTS

- Evaluating the biogeochemistry of enhanced mineral weathering on soils, including effect on microbes and productivity
- Exploring the role of deep roots in engineering soil properties and the role of perennial cropping in carbon removal and storage
- Examining the role of microbial stress tolerance and physical disturbances in soil carbon storage

Photo by Karsten Wurth

New Search - Environmental Engineering

The Center is currently collaborating with the Department of Chemical & Environmental Engineering in the School of Engineering and Applied Sciences (SEAS), on a new faculty search in the area of environmental engineering. The search committee is being chaired by one of the YCNCC scientific leadership members and the inaugural vice provost of the Planetary Solutions Project, Professor Julie Zimmerman (from both CEE/SEAS and YSE) and includes one of our new hires Professor Matt Eisaman. The new faculty member will be instrumental in building strong connections between the YCNCC and SEAS.

FACULTY SEARCH COMMITTEE

Julie Zimmerman

Professor of Chemical & Environmental Engineering, and of School of the Environment, and of Epidemiology (Environmental Health Sciences)

Jaehong Kim

Professor of Chemical and Environmental Engineering

Matthew Eisaman

Associate Professor of Earth & Planetary Sciences

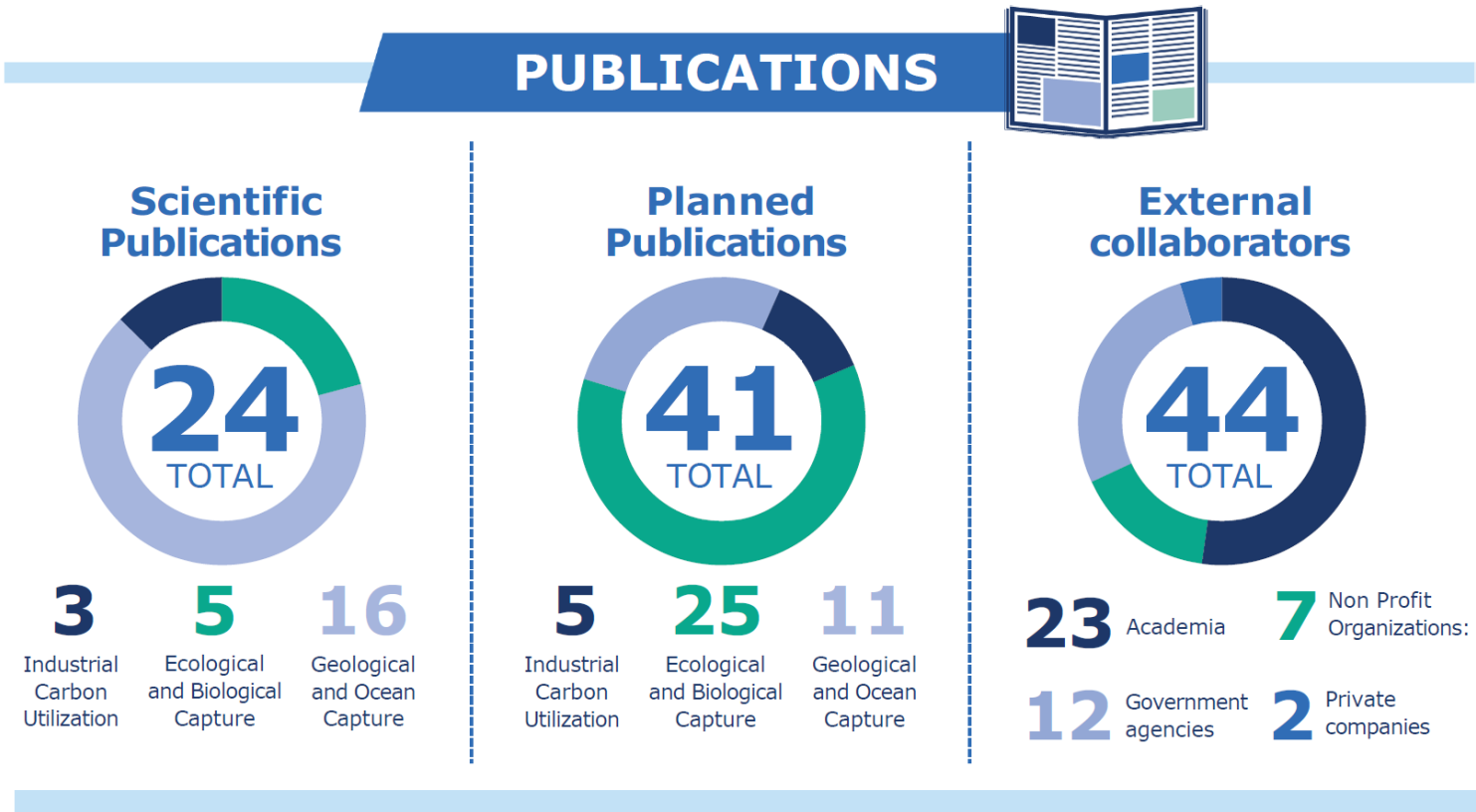
Drew Gentner

Diversity Representative

Associate Professor of Chemical & Environmental Engineering; Associate Professor, School of the Environment

Research Projects and Updates

This past year was defined by innovative and transformative efforts to advance natural carbon capture science through the Center's growing research network. The Center is proud to present a snapshot of the ongoing research efforts, which have unfolded across diverse landscapes to inform climate change mitigation strategies. Several noteworthy accomplishments have emerged from the Center in the past year. Amidst these accomplishments, two prominent initiatives have emerged: the Yale Applied Science Synthesis Program (YASSP) and revolutionary strides in enhanced rock weathering (ERW). Through these efforts, the Center has established itself as a global thought leader in climate change science, serving as a valuable nexus for collaboration with researchers, NGOs, government agencies, and corporations alike.



Ecological and Biological Capture: Blue Carbon

Coastal ecosystems – such as mangroves, marshes, and seagrass meadows – can be even more effective at capturing carbon than tropical forests on a per-unit-area basis, and their sediments likewise contain large amounts of stored carbon. But scientists still lack a complete understanding of the ways that the carbon in these ecosystems, often referred to as "blue carbon", is captured, stored, and released. Given the importance of coastal ecosystems and their vulnerability to both human disruption and extreme weather, the Yale Center of Natural Carbon Capture maintains a major research initiative focused on Blue Carbon and has funded several related research projects to investigate and establish the details of how carbon moves through these ecosystems.

The research conducted though these projects will illuminate critical aspects of the carbon cycle in coastal ecosystems and provide the scientific basis for implementing management practices that will directly impact their carbon capture and storage capacity. Each project investigates a distinct aspect of the of the carbon sequestration potential in these systems, from watershed scale experiments to mapping the occurrence of seagrass and mangrove ecosystems to understanding the impacts of temperature and other factors on carbon sequestration by algae.

Major Research Initiative: Blue Carbon

PI: Pete 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 Vaugh, postdoctoral associate
- Sophia Chirico, postgraduate associate
- Ben Girgenti, Master's student
- Michael Norton, postgraduate associate
- Moshema Hull, postgraduate associate
- Jessie Peterman, Master's student
- James Nikkel, Research Scientist, Physics Department
- Jordan Peccia, Thomas E. Golden, Jr. Professor of Environmental Engineering
- Frannie Adams, Master's student
- Alfia Ansari, New Haven Promise
- Gershon "Levi" Ariker, New Haven Promise
- Nikki Zhang, Master's student
- Emily Zhang, Master's student

Collaborators at other institutions:

- Chris Hunt, Research Assistant Professor, School of Marine Science and Ocean Engineering, University of New Hampshire
- Steve Malinowski, Fishers Island Oysters
- Wade McGillis, Professor of Civil and Environmental Engineering and Earth Sciences, College of Engineering, University of Notre Dame
- Charlie Driscoll, University Professor of Environmental Systems and Distinguished Professor, College of Engineering & Computer Science, Syracuse University
- John Pohlman, Research Chemist, Woods Hole Coastal and Marine Science Center
- Anne Giblin, Senior Scientist and Director, The Ecosystems Center, Marine Biological Laboratory
- Ben Poulter, Research Scientist, NASA Goddard Space Flight Center
- John Kominoski, Principal Investigator, Florida International University

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 gases stored in different components of these ecosystems and for how long.

This research is significant because coastal systems are increasingly impacted by human activities and 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. The Blue Carbon 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 established a “Blue Carbon Timescale Network”, the first global data set of the age of peat profiles. In addition, the team is collaborating on a watershed-scale experiment on alkalinity generation (which enhances carbon capture). They have measured alkalinity generation at marsh sites in New England and the Florida Everglades, as well as at Oyster Pond in Connecticut. The scientists have deployed instruments to measure alkalinity in the field at the CT River and are collaborating with the Sound School, a New Haven high school for aquaculture/agriculture science and technology education, on the "Living Laboratory" project. Additionally, they are building experimental structures called "oyster balls" with the Sound School to test their capacity for alkalinity generation and oyster recruitment.

In the area of ecosystems and methane (a powerful greenhouse gas), the team has completed six transects of the Long Island Sound, measuring methane and nitrous oxide and have also finished an experiment exploring the use of iron to decrease methane emissions from wetlands. Furthermore, they have completed a second transect of methane emissions in the Florida Everglades, focusing on a mangrove-dominated ecosystem and considering both aquatic and tree-based methane fluxes. Another focus is on assessing the connection between microbial community dynamics and methane production in trees.

Scientific outputs:

Through the Blue Carbon Timescale Network, our scientists are determining sequestration rates in natural and restored blue carbon ecosystems, which will be used to quantify potential carbon capture and storage rates under varying conditions. In addition, the group developed a prototype of an instrument to measure alkalinity in the field and successfully deployed a second prototype at a field site. The 14C-AMS carbon dating instrument, one of the first major investments made by YCNCC, is now operational, with initial tests and samples conducted, and plans for broader usage in the coming year. These advances in instrumentation will move the field forward by helping researchers more accurately measure carbon dynamics.

Funded Project: Developing a Blue Carbon Enhancement Plan for Sri Lanka

PIs: Graeme P. Berlyn, E. H. Harriman Professor at the School of the Environment and Anitra Thorhaug, President, Greater Caribbean Energy & Environment Foundation

Researchers at Yale:

- Kevin Gallagher, Master's student

Collaborators at other institutions:

- Ted Manning, President, Tourisk LLC. (Formerly Environment Canada)
- Hasanthi Dissanayake, Ambassador, Sri Lanka Foreign Affairs Office, Principle for Oceans & Climate Change
- Rifa Wawood, Sri Lanka Foreign Affairs Office, Co-Principal Oceans & Climate Change
- Rizvi Hassen, Sri Lanka Foreign Affairs Office, Oceans & Climate Change
- Sasikala Weijrawersandena, Attorney, Foreign Office Oceans & Climate Change
- Pathma Abeykoon, Director/Biodiversity Secretariat, Ministry of Environment
- Manjula Amararathna, Director (Protected Area Management), Department of Wildlife Conservation
- Nishantha Edirisnghe, Conservator of Forests, Forest Department
- Captain Bandara, Sri Lanka Navy, in charge nearshore resource stewardship.
- Professor Sevvandi Jayakody, Estuarine Mangrove Scientist Sri Lanka
- Avi Perwiti, Ph.D. German Space Agency
- Demosthenes Traganos, German Space Agency
- D.D.G.L.Dahanayaka, Seagrass Map in Mannar Bay
- Susantha Udagedara, NGO and Open University, Sri Lanka

Project overview:

Recent estimates suggest that seagrass meadows and mangroves in Southeast Asia and the Caribbean have the capacity to store more carbon than tropical forests. This project focuses on seagrass meadows and mangrove forests along the Sri Lankan coast, with three main goals:

1. Estimating the amount of captured carbon in coastal systems using satellite maps and field sampling.
2. Building a Sri Lanka Government agency coalition to approve the recommended future restoration and preservation plans to enhance blue carbon capture.
3. Creating detailed plans to support the Sri Lankan government agencies with implementing seagrass restoration plans and attracting additional funding for these efforts from outside sources.

First year accomplishments:

The team is in the final phase of generating a satellite-based map to measure the extent of seagrass, past areas of seagrass, estimates of blue carbon, bathymetry, fishing, recreational, and preserve areas. Sampling sites have been selected and preparations for the field work are in the final stage. Researchers have successfully worked with the Sri Lankan government on establishing sites for restoration projects and agreed on scope, goals, and participants for the pilot restoration projects.

Scientific outputs:

Created the first version of a publicly available web map of seagrass and mangrove occurrence in Sri Lanka (available at: https://aviputri.users.earthengine.app/view/east-sri-lanka-seagrass-map).

Funded Project: The Impact of Temperature, Grazing, and Acclimation on Algae

PI: David Vasseur, Professor, Professor of Ecology and Evolutionary Biology

Researchers at Yale:

- Carling Bieg, postdoctoral fellow

Project overview:

Algae are responsible for nearly half of the global carbon fixation and fundamental to bottom-up regulation of all aquatic systems. Carbon that is fixed into algal biomass is readily available as a food source for herbivores and it therefore quickly moves through the aquatic food chain. As a result, most of the carbon fixed by algae is returned to the atmosphere via respiration and only a small amount is ultimately sequestered in deep lake or ocean sediments. Changing temperatures due to global warming will alter the flow of nutrients and energy (carbon) in aquatic food webs and may therefore have substantial impact on the fate of fixed carbon in aquatic systems.

First year accomplishments:

In the first year of this project, the researchers have developed a new mathematical theory that describes the interconnected effects that nutrients and temperature have on algal production and biomass; they show that these cannot be considered independently, and they demonstrate several general principles that have yet to be integrated into large-scale predictive modeling frameworks. In the simplest terms, the potential for long-term carbon capture by aquatic systems depends on the rate at which biomass is sequestered naturally by sedimentation or artificially by harvesting and fixation. This rate is proportional to the product of size of the 'biomass pool' and on the per-capita rate of turnover of the pool. The theoretical work demonstrates that the per-capita rate of turnover increases with warming (so long as it does not induce thermal stress on algae). However, they also demonstrate that warming consistently decreases the size of the biomass pool leading to an important tradeoff that will limit any expected gains or losses in carbon sequestration due to warming. A key goal of the second year of the project is to deploy the theoretical model into a predictive framework and apply the findings toward scalable solutions for carbon sequestration.

Scientific outputs:

The team successfully developed a new theory for describing how changes in nutrients and temperature can influence algal production and biomass.

Ecological and Biological Capture: Terrestrial Ecosystems

Terrestrial ecosystems capture, cycle, and store tremendous amounts of carbon. Enhancing biological capture and storage of carbon in terrestrial ecosystems is one promising strategy for reducing atmospheric carbon. On land, these processes can occur through forest growth and agricultural soil restoration. Non-forested ecosystems such as grasslands, deserts, and shrublands are also important, storing very large quantities of carbon, though with slower rates of ecosystem carbon uptake.

The Yale Center for Natural Carbon Capture is funding several projects and initiatives that aim at understanding how different ecosystems cycle and store carbon and how different land use and management approaches affect carbon capture and storage in these systems. The Center maintains a major research initiative – the Yale Applied Science Synthesis Program – and funds several additional "on-the-ground" research projects. Each funded project addresses a different aspect in terrestrial ecosystems and individual systems' capacity for capturing and storing carbon. Several projects directly investigate how different management practices impact a system's carbon capture potential, while other projects investigate the underlying mechanisms determining carbon capture and storage potential in undisturbed or managed ecosystems.

Major achievements of the last year include:

- Successfully networking and collaborating with organizations across the globe representing public and private sectors
- Providing expert knowledge to decision-makers, practitioners, and other stakeholders
- Completion of literature reviews
- Establishment of field sites for long term monitoring and sampling campaigns
- Development of maps providing information about regional carbon capture potential to support planning and implementation of carbon capture projects and determine knowledge gaps
- Development of novel instrumentation to measure soil carbon emissions in the field
- Built life cycle assessment models for cross laminated timber and traditional construction materials

Major Research Initiative: Yale Applied Science Synthesis Program

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

Researchers at Yale:

- Sara Kuebbing, Research Scientist, YASSP Director of Research, Yale School of the Environment
- Cole Gross, postdoctoral associate, Yale School of the Environment
- Laura Toro, postdoctoral associate, Yale School of the Environment
- Lisa Eash, postdoctoral associate, Yale School of the Environment
- Luca Guadagno, postgraduate researcher
- Will Gardner, summer research fellow, School of Management and Yale School of the Environment
- Anna Stemberger, summer research fellow, Yale School of the Environment

Collaborators at other institutions:

- Jennifer Pett-Ridge, Senior Scientist, Group Leader, Environmental Isotope Systems Group (PLS, NACS), Lead Scientist, LLNL Soil Microbiome Scientific Focus Area, Lawrence-Livermore National Labs
- Mark Ducey, Chair & Professor, Department of Natural Resources and the Environment, University of New Hampshire
- Emily Oldfield, Agricultural Soil Carbon Scientist, Environmental Defense Fund
- Doria Gordon Senior Director, Lead Senior Scientist, Environmental Defense Fund

Project overview:

The Yale Center for Natural Carbon Capture provided funding to establish the Yale Applied Science Synthesis Program in 2021. The program facilitates collaboration among academic researchers, policymakers, and land managers to address questions related to the impact of land management decisions on the services rendered by various natural landscapes, including forests, croplands, wetlands, rangelands, and grasslands.

The Program's primary focus revolves around assisting both for-profit and not-for-profit partners in adopting sustainable land management practices. Through the Program's synthesis work, researchers concentrate on the regional context in which local management decisions are made. This approach allows them to optimize the benefits derived from these land resources, such as carbon storage, sustainable food production, and biodiversity preservation. The Program generates applied scientific knowledge that guides effective stewardship of forests and natural landscapes. The Program is driving five different projects forward, each with the goal of providing robust information for land management practices to practitioners and decision makers:

- *Impacts of Commercial Plantations in South & Central America on forest carbon budgets:* This project focuses on monoculture tree plantations in South and Central American countries, which play a significant role in the economy. The impact of these plantations on carbon emissions depends on the management and policy frameworks in place, as they can either contribute to carbon emissions from natural forest loss or act as carbon sinks with effective national-level land use planning and regulation policies. The project highlights the wide variation in how different countries include plantation forest management in their climate mitigation goals.
- *Model development and estimation of baseline carbon stocks in cranberry farm ecosystems:* This project focuses on cranberry farm ecosystems in several US states and Canadian provinces, which are significant economic commodities often located near or on natural wetlands with large carbon stocks. Despite their small global land area, cranberry farms likely store a substantial amount of soil carbon, especially when situated over peat and supported by landscapes like forests, grasslands, and wetlands that can also sequester carbon.

The project aims to estimate carbon storage in these systems and review the ecosystem services they offer, considering different management practices.

- *Roads to Removal: Sustainable Forest Management for Carbon Dioxide Removal:* This project focuses on the importance of forest management as a scalable and cost-effective approach for climate mitigation and reducing net carbon in the atmosphere. The project emphasizes the need for customized management activities that consider the unique ecology, environment, economy, and culture of diverse forested lands and the communities that rely on them for various services and goods provided by forests.
- *Agricultural Soil Carbon Monitoring, Reporting and Verification (MRV) Protocol Benchmark Analysis:* This project focuses on analyzing the variation in soil carbon Monitoring, Reporting, and Verification (MRV) protocols and how they affect the generation of carbon credits. The study explores the different criteria for additionality, baseline definition, greenhouse gas boundaries, uncertainty deductions, and buffer pool contributions among these protocols, impacting the eligibility of producers in soil carbon markets.
- *Is it Feasible to Quantify the Effect of Agricultural Practices on Soil Carbon Stocks through Sampling?* This project aims to address the debate surrounding the potential of regenerative practices to sequester soil carbon for climate change mitigation. By conducting high-density sampling on 45 cropland fields, the project evaluates the assumption that within-field variation in stock sizes makes it infeasible to accurately quantify incremental carbon accrual.

First year progress:

Several noteworthy achievements have emerged from diverse the projects that advanced over the past year:

Impacts of Commercial Plantations in South & Central America on forest carbon budgets:

For this project, researchers worked directly with 'The Forest Dialogue' at Yale to establish networks and structures for engaging directly with landowners and land managers on implementing forest management practices. They have drafted a scoping document for facilitating dialogue with relevant organizations in Central and South America and attended a workshop with plantation owners in Indonesia.

Researchers are establishing a network of conservation groups, such as The Nature Conservancy, and helping improve the data these organizations use for planning and implementing their conservation projects.

Model development and estimation of baseline carbon stocks in cranberry farm ecosystems:

Researchers worked directly with Ocean Spray, supporting Ocean Spray's engagement in the voluntary carbon market and helping with providing information to other stakeholders about soil carbon and natural climate solutions.

Roads to Removal: Sustainable Forest Management for Carbon Dioxide Removal:

A new draft chapter is out for review and will be published and rolled out nationwide in September.

Agricultural Soil Carbon Monitoring, Reporting and Verification (MRV) Protocol Benchmark Analysis:

Over the past year, the researchers at the Yale Science Synthesis Program have established an extensive network of soil carbon scientists who are now collaboratively working towards defining best practices for measuring soil carbon and including this information in the creation of carbon standards.

Additionally, researchers have commented on Requests for Information and have been invited as technical experts for the Clean Air Task Force to provide expertise on carbon crediting.

Is it Feasible to Quantify the Effect of Agricultural Practices on Soil Carbon Stocks through Sampling?

Recent findings by the team show the feasibility of monitoring soil carbon stock responses to practice change and provide recommendations for data that government, farmers, and corporate entities should measure and share. This will build confidence in the effectiveness of regenerative practices, moving away from overreliance on theoretical data collected at scales not aligned with agricultural management.

Scientific outputs:

Researchers of the Yale Applied Science Synthesis Program have participated in and contributed to various activities and documents that directly shape policy and implementation of best practices for land management and carbon capture (for a detailed list please see the section Programs and Activities: Outreach and Engagement).

In addition, the following manuscripts were published:

1. Tan, SX and SE Kuebbing. "A synthesis of the effect of regenerative agriculture on soil carbon sequestration in Southeast Asian croplands." Agriculture, Ecosystems & Environment, vol. 349, 2023, 108450.
2. Panwar, R and L Toro. "The forest sector and ecosystem restoration." Restoration Scoping Dialogue. The Forests Dialogue, 2023.

Funded Project: Sequestering Carbon through Protection and Production: A Case Study of Industrial Reforestation in Mata Atlantica, Brazil

PI: Mark Ashton, Senior Associate Dean of The Forest School; Morris K. Jesup Professor of Silviculture and Forest Ecology; Director of Yale Forests, Yale School of the Environment

Researchers at Yale:

- Yuan Yao, Assistant Professor, Yale School of the Environment
- Luke Sanford, Assistant Professor, Yale School of the Environment
- Owen Cortner, postdoctoral associate, Yale School of the Environment
- Fan Yang, postdoctoral associate, Yale School of the Environment

Collaborators at other institutions:

- Daniel Piotto, Dean, Federal University of Southern Bahia, Department of Agroforestry and Forest Ecology

Project overview:

To date the scientific literature does not provide any information about any studies that have examined the potential synergies of industrial reforestation with secondary forest regrowth. This project examines this potential by investigating:

1. The role industrial plantations can play in both elevating the carbon stored in soils and above ground biomass as compared to former and current agricultural and pastoral lands
2. The potential for long-term carbon storage in manufactured wood products
3. The potential for these wood products to be substitutes for more energy intensive materials
4. The potential of these wood products to restore and protect recovering second growth within the reforestation area

This project is carried out through a collaboration of three different research teams investigating the above questions from various angles:

Ashton and Piotto Group: This group is measuring the effect of the Brazilian Forest Protection Code (BFPC) on increasing native forest cover in the Mata Atlantica region in relation to different land uses – in particular on tree plantations and pasture. They are determining the reforestation effect on standing carbon in production and protection forest as compared to the main de-facto land use – pasture. Lastly, they are developing and implementing a pixel-based counterfactual estimation strategy to assess the overall impact of commercial reforestation and the effect of each eucalyptus stand.

Sanford Group: This group is gathering remote sensing and economic and administrative data to understand how the Veracel Mill and land purchasing has affected ecosystem carbon through land use. In particular, researchers are estimating carbon stored in eucalyptus plantations, mature secondary forest, and regenerating secondary forest. The goal is to understand the net carbon consequences of the establishment of the pulp and paper mill, and whether tree plantations can help encourage secondary forest regeneration—especially when implemented on pastureland.

Yao Group: The carbon sequestration due to different reforestation plans and wood utilizations is quantified using Life Cycle Assessment. The system boundary of Life Cycle Assessments for long-lived wood products and paper products will include all unit processes involved in forest management, harvesting, production, transportation, use phase (e.g., construction and use of wood products in buildings, distribution, and use of papers), and end of life.

First year progress:

The Ashton group has successfully established two permanent forest research plots in the study region. They completed extensive field work including collecting 270 GPS points for ground truthing remote data, measured and tagged individual trees in the two research plots, collected leaf litter and data on other key variables. The team also created inventories at 15 variable plots in secondary forest stands and collected more relevant data in the field.

They established points of contact with staff at Veracel Celulose and the staff at the RPPN Estação Veracel - UNESCO World Natural Heritage, where they acquired details on pulp mill operations, chemical inputs, and energy consumption as inputs data for life cycle assessment modelling.

The team working with Yuan Yao has competed a comprehensive literature review of emerging and existing eucalyptus-based wood products, along with exploring different models for simulating eucalyptus growth and yield. The group has collected life cycle inventory data of manufacturing wood products and pulp and paper in Brazil.

The Sanford team has used remote sensing data, and data from the MapBiomas platform for establishing an understanding of overall land use in the area and combined this with ground truth points.

Scientific outputs:

Established and measured tree plots at field sites in Brazil, collected remote sensing and economic and administrative data for the area, and developed Life Cycle Assessment models for this system.

Funded Project: Climate Benefits of Releasing Degraded Hardwood Forests From Liana Loading

PI: Mark Ashton, Morris K. Jesup Professor of Silviculture and Forest Ecology and the Director of the Yale Forests, Senior Associate Dean of The Forest School at the Yale School of Environment.

Researchers at Yale:

- Jacob Peters, PhD Student, Yale School of the Environment
- Xuhui Lee, Sara Shallenberger Brown Professor of Meteorology, Yale School of the Environment

Collaborators at other institutions:

- Bronson Griscom, Senior Director of Natural Climate Solutions, Conservation International

Project overview:

This project focuses on using drones, remote sensing, and field methods to study how woody vines affect temperate forest growth and carbon storage rates. Focusing on forests across North Carolina, researchers will study many different forest types with varied land use histories. Along forest edges (roadsides, agricultural fields, etc.), they will use a drone-mounted camera to create three-dimensional and high-resolution images of the forest canopy, allowing them to distinguish between dead trees, canopy gaps, healthy trees, vines, and other surface features. Finally, they use field experiments to test the benefits, drawbacks, and cost of cutting vines as a forest management practice. The experts are also focusing on using remote sensing and machine learning techniques (via Google Earth Engine) to map vines across forests of the United States.

First year progress:

Researchers have established close collaborations with the US Forest Service, local governments, small landowners, and universities in North Carolina to search for potential field sites across the state. The group has worked on creating species distribution maps for several key liana species (e.g., kudzu, honeysuckle, bittersweet, and grape), with the intention of adding more species in the future. Additionally, they have recently acquired a drone and a multispectral high-resolution camera to map field plots and test liana classification methods.

Scientific outputs:

The group completed a comprehensive literature review on various aspects of liana (woody vine) biology, including impacts, history, treatment, and biogeography, to complement and help refine plans for field measurement.

Funded Project: Capacity To Recover – Carbon Storage and Capture in the Sinharaja Land Use Mosaic (Sri Lanka)

PI: Luke Sanford, Assistant Professor of Environmental Policy and Governance, Yale School of the Environment

Researchers at Yale:

- Dr. Mark Ashton, Senior Associate Dean of The Forest School; Morris K. Jesup Professor of Silviculture and Forest Ecology; Director of Yale Forests, Yale School of the Environment
- Dr. Simon Queenborough, Senior Lecturer and Research Scientist; Musser Director, Tropical Resources Institute, Yale School of the Environment
- David Woodbury, Ph.D. Candidate, Yale School of the Environment

Collaborators at other institutions:

- Sisira Ediriweera, Professor of Forest Ecology, Uva Wellasa University
- The Sri Lanka Program for Forest Conservation, Nugegoda, Sri Lanka

Project overview:

This project focuses on studying tropical forests in South and Southeast Asia, which have a high carbon storage capacity per unit area. The research investigates how forest clearance for plantation agriculture 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 study site 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. 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 in forest mosaic landscapes based on their land use and ownership history.

First year progress:

The team measured biomass in 179 field plots in small secondary forest fragments, tea plantations, rubber plantations, and pine plantations. Additionally, the team used aerial photographs prior to 1983 to create a mosaic of the study landscape. Last summer, three Yale School of the Environment Master's students evaluated the local social and land use changes and estimated the above-ground carbon within the region's tree gardens and tea plantations.

Scientific outputs:

New data on above-ground forest carbon was collected from multiple field sites to contribute to a comprehensive characterization of carbon storage in different natural and managed forest types in the region.

Funded Project: Moose Management for Enhancing Boreal Forest Carbon Storage

PI: Oswald Schmitz, Oastler Professor of Population and Community Ecology, Yale School of the Environment

Researchers at Yale:

- Elizabeth Forbes, postdoctoral fellow
- Urmila Mallick, incoming PhD student, current Master's student
- Janey Lienau, incoming PhD student, current Master's student
- Vivian Hawkinson, Master's student
- Brandon Lee, undergraduate research technician, Yale School of Engineering and Applied Science
- Dr. Aaron Dollar, Yale School of Engineering and Applied Sciences
- Connor Pan, PhD student, Yale School of Engineering and Applied Sciences

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 ecosystems' carbon dynamics, this study highlights the importance of animals, from small to large, in influencing carbon uptake and storage within ecosystems. The research specifically focuses on moose, a large-bodied vertebrate, and aims to quantify how moose population densities and forest disturbance regimes 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.

First year progress:

During a successful pilot field season in summer 2022, researchers collected preliminary data in Terra Nova National Park in Newfoundland, Canada. The data collection focused on in-situ soil carbon flux rates across various forest disturbance types and moose population densities. The researchers also gathered metadata to assess the factors influencing these variables, including canopy cover, vegetation community, soil organic layer depth, and soil temperature/moisture.

Lab work revealed spatial variability in soil carbon flux and the influence of moose density and canopy disturbance on soil nitrogen and carbon content. The project involves collaboration with Dr. Aaron Dollar and PhD student Connor Pan to develop a "Fluxbot" for continuous monitoring of soil carbon emissions in the park. Carbon dioxide sensor accuracy was tested by Dr. Forbes and Dr. Ravish Dubey, while Connor Pan contributed remote data transmission code. Vatsal Patel designed a cost-effective 3D-printed lid mechanism, and leak tests were performed for functionality assurance. An array of Fluxbots was constructed for installation in the field during summer 2023.

Scientific outputs:

Established a collaboration with Dr. Aaron Dollar (Yale School of Engineering and Applied Sciences) along with a first-year PhD student in his lab (Connor Pan) who is working with Dr. Forbes to redesign and construct her "Fluxbot." This novel instrument is capable of monitoring continuous, real-time soil carbon emissions rates. The researchers will use it across a range of moose population densities and canopy disturbance types for measuring carbon emission rates.

Funded Project: Molecular Tools for Resolving Biological CH4 Production and Uptake in Natural Systems

PI: Jordan Peccia, Thomas E. Golden, Jr. Professor and Chair of Chemical & Environmental Engineering, Yale School of Engineering & Applied Science

Researchers at Yale:

- Peter Raymond, Professor, Yale School of the Environment
- Mark Branford, Professor, Yale School of the Environment
- Craig Brodersen, Professor, Yale School of the Environment
- Marlyse Duguid, Senior Lecturer, Yale School of the Environment
- Wyatt Arnold, SEAS PhD student
- Jonathan Gewirtzman, YSE PhD student
- Cade Brown, undergraduate researcher, Yale Department of Chemical and Environmental Engineering

Collaborators at other institutions:

- Qespi T'ika Wood, summer undergraduate researcher, Universidad Nacional de San Antonio Abad del Cusco, Peru

Project overview:

This project aims to study methane emissions from soils, wetlands, and inland waters, which contribute to >30% of global methane emissions. Microbial activity in these environments produces methane, and with changing climate conditions, these emissions are expected to increase. The project focuses on understanding the dynamics of methane production and degradation by specific groups of bacteria, called methanogens and methanotrophs, respectively. To achieve this, the researchers will develop and validate gene-based tools that can quantify methane production and degradation rates separately. The first application of these tools will be to determine whether methane is produced or degraded in tree tissues. This knowledge is essential for accurate carbon accounting in forests, which influences global climate models, carbon markets, and emission targets. Understanding methane dynamics in different environments will contribute to a better understanding of its impact on the atmosphere and help inform climate change mitigation strategies.

First year progress:

The team has analyzed samples from over 125 healthy hardwood and softwood trees in the Northeastern US and confirmed the release of methane from tree wood into the atmosphere. They have also measured methane concentrations within the tree itself. The experiments and measurements showed that methane is generated by and within threes, and the group gained insights into the quantity of methane produced by live trees. These findings indicate that this process predominantly occurs in the heartwood of trees.

Scientific outputs:

The following manuscripts were submitted for publication:

1. Arnold, W., et al. "Extraction of microbial nucleic acids from live tree wood." For submission to New Phytologist, summer 2023.
2. Arnold, W., et al. "Fungal and bacterial ecology of live wood." For submission Fall 2023.
3. Gewirtzman, J., et al. "Microbial mechanisms of CH4 production and flux in live, upland trees." For submission Fall/Winter 2023.

Funded Project: The Natural Carbon Consequence of Cross Laminated Timber

PI: Yuan Yao, Assistant Professor of Industrial Ecology and Sustainable Systems, Yale School of the Environment.

Researchers at Yale:

- Robert Mendelsohn, Edwin Weyerhaeuser Davis Professor of Forest Policy; Professor of Economics; and Professor, School of Management
- Alice Favero, Senior Environmental Economist, RTI International
- Kai Lan, postdoctoral associate, Yale School of the Environment
- Hannah Wang, Ph.D. student, Yale School of the Environment

Project overview:

This project focuses on cross-laminated timber (CLT), an emerging wood product used in mid- and high-rise buildings that can store carbon and help mitigate climate change by replacing carbon-intensive construction materials. However, concerns exist about the potential impact of increased wood harvests on forest carbon storage and the carbon emissions associated with cross-laminated timber manufacturing and disposal. 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 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.

The integrated analysis aims to determine the role of timber, particularly CLT, in climate change mitigation as a nature-based solution. 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.

First year progress:

The group has built life cycle assessment models for cross laminated timber production, end-of-life, and traditional wood products derived from sawtimber and pulpwood. They also developed life cycle assessment models for traditional construction materials for estimating the cross laminated timber substitution benefits. The team has set up and successfully run the global timber model to simulate global forest lands and carbon for the years 2020 to 2100. They estimated cross laminated timber demands in the future based on the various demand levels and adoption speeds for 16 world regions and generated preliminary regional and global results for net greenhouse gas balances and carbon stock changes.

Scientific outputs:

The group has built multiple life cycle assessment models and generated preliminary regional and global results for net greenhouse gas balances and carbon stock changes. Yao presented this project to the Department of Chemical Engineering at Michigan Technological University and at the Planetary Solutions Spring Showcase at Yale.

Geological Capture: Enhanced Rock Weathering

Some of the most abundant minerals on Earth's surface can be added to soils and potentially remove billions of tons of carbon dioxide from the atmosphere per year. Basalt—a common volcanic rock—is especially rich in such minerals that can effectively react with carbon dioxide through the process of weathering (erosion combined with the reaction of minerals with CO_2 dissolved in water in the form of carbonic acid), eventually leading to permanent carbon dioxide storage as carbonate minerals (like limestone). Most of the surface carbon on our planet is stored this way (the Cliffs of Dover and elsewhere in the south of England are good examples). The Yale Center for Natural Carbon Capture supports multiple projects and initiatives that investigate ways to speed up and track basalt's carbon-absorbing reactions, through enhanced weathering, helping to establish an extremely promising and scalable form of durable carbon capture.

Weathering can be enhanced by crushing basalt, increasing its surface area so that more of the rock can come into contact with the carbon dioxide dissolved in soils. Much of the carbon removed from the atmosphere, now in a harmless form called bicarbonate, eventually ends up in the oceans, where it can safely remain for tens of thousands of years. Eventually the bicarbonate forms stable carbonate minerals through interaction with minerals and sediments as well as through shell and reef production. This process also reduces ocean acidity and promotes coral health, therefore adding a vital co-benefit.

Various organizations investigate this globally; at Yale the Center for Natural Carbon Capture has funded several projects and a symposium on the topic. Each project investigates different aspects of this process and under various conditions in the field, using field and lab measurements, modeling, and other methods for determining the practicality and effectiveness of enhanced rock weathering.

<u>Major first year accomplishments include:</u>

- Developing new estimates for the carbon capture potential from enhanced weathering in the US and globally and developed new estimates of cardon dioxide release back into the atmosphere after initial capture
- Throughout the past year the researchers have established a wide collaboration with modeling and enhanced weathering experts at various institutions across the globe
- Helping initiate a project for comparing enhanced weathering reactive transport models with the goal of establishing consensus on the models to be used for estimating the carbon capture and storage rates
- Connecting representatives from academia, private, and public sectors to collaboratively advance the science and implementation of enhanced rock weathering techniques for reducing greenhouse gas concentrations

Major Research Initiative: Harnessing Natural Basalt Weathering to Capture CO_2 in Agricultural Settings

PI: Noah Planavsky, Professor of Earth & Planetary Sciences, Department for Earth and Planetary Sciences

Researchers at Yale:

- James Saiers, Clifton R. Musser Professor at the School of the Environment and Professor of Geology and Geophysics, Yale School of the Environment
- Peter Raymond, Professor and Senior Associate Dean of Research at the School of the Environment and Professor of Earth and Planetary Science, Yale School of the Environment
- Yuan Yao, Assistant Professor, Yale School of the Environment
- Juan Lora, Assistant Professor, Department of Earth and Planetary Sciences
- Boriana Kalderon-Asael, research assistant
- Fengchao Sun, postdoctoral associate, Yale School of the Environment
- Jiuyuan Wang, Agouron Postdoctoral Fellow, Department for Earth and Planetary Sciences
- Jesper Suhrhoff, postdoctoral fellow, Department for Earth and Planetary Sciences
- Evelin Pihlap, postdoctoral associate, Department for Earth and Planetary Sciences
- Marya Matlin-Wainer, postgraduate research associate
- Ayesha Ahmed, graduate student
- Brian Beaty, graduate student
- Isabella Chiaravalloti, graduate student
- Chloe Kent, graduate student
- Jennifer Kroeger, graduate student
- Tom Reershemius, graduate student
- Gavrielle Welbel, student employee, Yale Sustainable Food Program
- Kaylea Nelson, Team Lead of Computational Research Support, Center for Research Computing, Yale University

Collaborators at other institutions:

- David J. Beerling, Professor of Natural Sciences, University of Sheffield
- Yoshiki Kanzaki, postdoctoral fellow, School of Earth & Atmospheric Sciences, Georgia Institute of Technology
- Christopher T. Reinhard, Associate Professor, Georgia Institute of Technology
- Shuang Zhang, Assistant Professor, Texas A&M

Project overview:

This project investigates the effects of incorporating milled basalt rock into various agricultural settings, wherein the small grain size (hence more reactive surface area) of pulverized minerals is what leads to enhanced mineral weathering. Ongoing efforts involve exploring the potential of CO_2 removal in agricultural lands and developing methods to track and quantify enhanced rock weathering to ensure long-lasting CO_2 removal effects.

Researchers are conducting field trials where ground-up minerals are added to fields growing different crops. They then measure carbon uptake via plant productivity, soil carbon storage, and downstream transport through watersheds to the ocean. Laboratory analyses and a review of existing scientific literature complement the field trials.

Enhanced Rock Weathering (ERW) in agricultural systems offers the potential for substantial carbon capture along with multiple co-benefits for food security, soil health, and economic stability for food producers.

Last year's progress:

Researchers developed a novel method for tracking enhanced rock weathering carbon capture and storage rates and completed a multiple year demonstration of carbon capture and the first demonstration that this method can decrease nitrous oxide fluxes.

The team developed new estimates for the carbon capture potential from enhanced weathering in the US and globally and developed new estimates of cardon dioxide release back into the atmosphere after initial capture.

They also completed a full analysis of the required field sampling density to reliably estimate carbon capture and storage in an area and a new life cycle assessment of enhanced rock weathering in the midwestern US.

Future plans to expand the field programs to explore scalability, measurement and verification of carbon uptake are currently in discussion with the YCNCC leadership.

Scientific outputs:

1. Cheung, C.T.L., et al. "Evaluating bedrock influences on chemical weathering via a comparative study between tropical rivers in Hong Kong and Marianas Islands." 2022 Goldschmidt Conference. GOLDSCHMIDT, 2022.
2. Chiaravalloti, I., et al. "Mitigation of soil nitrous oxide emissions during maize production with basalt amendments." Frontiers in Climate, vol. 5, 2023, 1203043.
3. Fakhraee, M., et al. "A biogeochemical model of mineral-based ocean alkalinity enhancement: impacts on the biological pump and ocean carbon uptake." Environmental Research Letters, vol. 18, 2023, 044047.
4. Fakhraee, M., Planavsky, N.J., and Reinhard, C.T. "Ocean alkalinity enhancement through restoration of blue carbon ecosystems." Nature Sustainability, vol. 1, 2023, pp. 1-8.
5. Kanzaki, Y., Planavsky, N.J., and Reinhard, C.T. "New estimates of the storage permanence and ocean co-benefits of enhanced rock weathering." PNAS Nexus, vol. 2, 2023, pgad059.
6. Kanzaki, Y., et al. "Soil Cycles of Elements simulator for Predicting TERrestrial regulation of greenhouse gases: SCEPTER v0. 9." Geoscientific Model Development, vol. 15, 2022, pp. 4959-4990.
7. Planavsky, N., et al. "Alkalinity enhancement and carbon capture potential in blue carbon ecosystems." AGU Fall Meeting Abstracts, 2022, pp. GC32I-0708.
8. Reershemius, T., et al. "A new soil-based approach for empirical monitoring of enhanced rock weathering rates." arXiv preprint arXiv:2302.05004, 2023.
9. Reershemius, T., et al. "Quantifying carbon dioxide removal in an enhanced rock weathering field trial in Queensland, Australia: a soil-based mass balance approach." Goldschmidt 2023 Conference. GOLDSCHMIDT, 2023.
10. Reinhard, C.T., et al. "Environmental impacts and carbon capture potential of mineral-based ocean alkalinity enhancement." Fall Meeting 2022. AGU, 2022.
11. Wang, J., et al. "An investigation of factors affecting high-precision Sr isotope analyses (87Sr/86Sr and δ88/86Sr) by MC-ICP-MS." Chemical Geology, vol. 621, 2023, 121365.
12. Welbel, G., et al. "Enhanced Rock Weathering in Agricultural Settings: Real-World Analysis of Carbon Dioxide Removal, Crop Yields, and Soil pH." Goldschmidt 2023 Conference. GOLDSCHMIDT, 2023.
13. Zhang, S., et al. "River chemistry constraints on the carbon capture potential of surficial enhanced rock weathering." Limnology and Oceanography, vol. 67, 2022, pp. S148-S157.

Funded Project: Calibrating Enhanced Rock Weathering with Os and Sr Isotopes

PI: Alan Rooney, Assistant Professor, Yale Department for Earth and Planetary Sciences

Researchers at Yale:

- Carey Ciaburri, PhD student, Yale Department for Earth and Planetary Sciences

Collaborators at other institutions:

- Drew Syverson, Research Scientist, Department of Geography and Earth Sciences, University of North Carolina, Charlotte

Project overview:

Enhanced rock weathering has the potential to both increase crop yields and actively remove greenhouse gasses from the atmosphere. However, our ability to accurately track how much carbon dioxide would be removed by this method is still an active area of research.

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 carbon dioxide removal from enhanced mineral weathering using basalts and identify any practical limitations. The data this project will generate will provide critical information to identify the parameters necessary for the most cost-effective and efficient ways to remove harmful greenhouse gasses from our atmosphere.

First year progress:

The researchers collected water samples from the watershed site of the ERW field program, with the aim to evaluate the geochemical properties of the water, specifically focusing on the neodymium (Nd), osmium (Os), and strontium (Sr) systems with which the transfer of carbon through various reactions can be traced. In addition, basalts were analyzed as potential feedstocks for the field sites. The team then successfully developed the modeling structures for field site reactions and designed greenhouse experiments that will be conducted during the second year.

Scientific outputs:

New aqueous geochemical data was obtained to characterize elemental composition, and potential carbon sinks were identified. Long-term infrastructure efforts were also carried out to facilitate future field work experiments.

Funded Project: Evaluation of Modeling Approaches for Enhanced Weathering

PI: Edward W. Bolton, Senior Research Scientist, Department of Earth and Planetary Sciences, Yale University

Researchers at Yale:

- Noah Planavsky, Associate Professor, Department of Earth and Planetary Sciences, Yale University
- Juan Lora, Assistant Professor, both at the Department of Earth and Planetary Sciences, Yale University
- Kaylea Nelson, Team Lead of Computational Research Support, Center for Research Computing, Yale University

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
- Michael E. Kelland, PhD Student, School of Biosciences, University of Sheffield
- Euripides P Kantzas, Research Scientist, 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 fellow, School of Earth & Atmospheric Sciences, Georgia Tech
- Shuang Zhang, Assistant Professor, Texas A&M University

Project overview:

Various scientific modeling efforts are designed to predict and estimate the amount of carbon captured and stored through enhanced rock weathering on agricultural lands. Given the complexity of the system, estimates from different models have produced a range of CO_2 removal estimates. Comparison between theory and experiments will refine these important model predictions, which will help guide field efforts.

This project focuses on exploratory pilot research to compare carbon dioxide removal estimates used for enhanced rock weathering in agricultural zones. Researchers are comparing several key reactive transport models with the goal of elucidating what factors lead to the differences in CO_2 removal estimates. They compare these models for a wide range of soil conditions, temperature, and the mineralogy and grain-size distributions of crushed basalts applied to agricultural soils. They also plan to compare model results over the course of a year on a grid of agricultural zones in the United States using measured daily rainfall and temperature to assess the influence of real time-dependent conditions. Finally, the project also assesses the influence of heterogeneities in the soil permeability field that is beyond what current models estimate. Results of this study will aid in the design of optimal techniques for preparing and applying crushed basalts to agricultural soils as a means of scalable carbon capture.

First year progress:

The group played a significant role in initiating the RockMIP project, which focuses on comparing enhanced weathering reactive transport models. The project aims to establish a consensus on the models to be used for estimating the carbon capture and storage rates. Each model's capabilities were outlined, specifically in relation to chemical and biological processes, hydrologic processes, minerals, and weathering. One frequently used model, the Kinflow model, was updated to incorporate sorption processes, and a version of Kinflow was developed to incorporate vapor diffusion

processes for soil simulations. Input files were prepared to compare the models to agricultural soils, and the code was tested using various soil targets.

Scientific outputs:

Throughout the first year of the project the researchers have established a wide collaboration with modeling and enhanced weathering experts at various institutions.

Funded Project: A Theoretical Framework To Assess the Realistic Potential for Carbon Mineralization

PI: Jun Korenaga, Professor of Earth & Planetary Sciences, Department for Earth and Planetary Sciences

Project overview:

This project aims to understand small scale processes that determine carbon capture and storage through enhanced weathering. 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 analysis for potential carbon mineralization solutions, advancing the understanding and application of this approach for CO_2 removal and sequestration.

First year progress:

Professor Korenaga has developed a simple theoretical model to examine the interaction between chemical reactions and the formation of crack porosity. This model allows for an assessment of how chemical reactions contribute to the formation of cracks in a material. He was able to derive a robust theoretical understanding the maximum depth that can be accessed by in situ carbon mineralization.

Ocean Capture and Alkalinity Enhancement

The oceans absorb more than a quarter of all carbon dioxide emitted by human activities, making it a crucial buffer against climate change. Scientists at the Yale Center for Natural Carbon Capture are looking for ways to safely increase the amount of carbon that the ocean can store. One method for this is ocean alkalinity enhancement which involves adding substances with high alkalinity, such as certain types of rocks or minerals, to the ocean. When these substances dissolve, they increase the ocean's alkalinity, which can lead to the absorption and storage of more carbon dioxide from the atmosphere. Ocean alkalinity can also be controlled by electrochemical techniques, which is the research program of our new faculty member Professor Matt Eisaman.

The idea behind ocean alkalinity enhancement is to enhance the natural ability of the oceans to act as a carbon sink, helping to reduce the overall concentration of CO_2 in the atmosphere and potentially mitigating the impacts of climate change. This approach is a rapidly growing area of international interest given its global potential and requires a robust and sizable effort toward research and development to assess its scalability, cost and its potential environmental impacts and co-benefits.

In addition to building a new effort around our new faculty member Matt Eisaman, the Center has funded two projects on ocean carbon dioxide removal through applications of minerals to enhance alkalinity, and through using microbially induced carbonate precipitation.

Major Research Initiative: Ocean-Based Carbon Capture and Storage: Investigating the Role of Ocean Processes in Governing Enhanced Mineral Weathering

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, Yale Center for Natural Carbon Capture
- Yiming Guo, postdoctoral researcher, Yale Center for Natural Carbon Capture

Project overview:

This project aims to investigate the ocean environment to understand the mechanisms and potential for large-scale carbon removal through ocean alkalinity enhancement. One approach involves spreading finely crushed minerals (rock dust) in the ocean to draw carbon dioxide out of the atmosphere. The research focuses on analyzing various processes, such as surface waves, ocean-atmosphere gas exchange, and ocean mixing, that directly influence this type of ocean-based carbon removal.

The main goals of the project are to quantify the effects of rock dust input in a dynamic ocean environment under different marine conditions and to understand how ocean processes impact the effectiveness of mineral weathering and its carbon storage potential. By identifying optimal marine settings for efficient carbon drawdown and understanding potential negative consequences of enhanced mineral weathering in the oceans, the results will contribute to scalable climate solutions. This project lays the groundwork for potential field experiments in the future, and its findings will play a crucial role in advancing our understanding of ocean-based carbon removal strategies for climate change mitigation.

First year accomplishments:

This research, which combines observational datasets with high-resolution ocean simulations, has revealed a new hybrid regime. This hybrid regime covers about 15% of the global ocean and exhibits notably high carbon dioxide uptake rates. The is continuing the research to study the relevant physics and implications of this hybrid regime, involving analysis of observations and numerical modeling.

Scientific outputs:

The following manuscripts were published:

1. Yang, A., J. Olsthoorn, and M.-L. Timmermans. "Sedimentation in particle-laden flows with and without velocity shear." In review, Physics of Fluids, 2023.
2. Guo, Y. and M.-L. Timmermans. "Surface pCO_2 variation regimes in the global ocean." In revision, Geophysical Research Letters, 2023.

Funded Project: An Integrated Biorefinery Pathway for Carbon Dioxide via Biologic Carbon Fixation

PI: Julie Zimmerman, Professor of Chemical & Environmental Engineering, Environment and Epidemiology, Yale School of Engineering & Applied Science

Researchers at Yale:

- Shu Hu, Assistant Professor, Dept. of Chemical and Environmental Engineering
- 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

Project overview:

This project aims to explore a novel approach for carbon dioxide 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 carbon dioxide 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 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.

First year progress:

During the first year of the project the team designed and constructed a novel headspace bioreactor, published a perspective piece discussing an ocean-based, microbial-electrochemical approach for simultaneous carbon fixation and carbonate precipitation. We also demonstrated atomic layer deposition (ALD) growth on membrane substate and subsequent surface characterization and determined atomic layer deposition Membrane Design Principles

Scientific outputs:

The following manuscript was published:

1. Kludze, Atsu, et al. "Biocement from the ocean: Hybrid microbial-electrochemical mineralization of CO_2." iScience, vol. 105156.

Industrial Carbon Utilization

The utilization of waste to make valuable materials is a primary tenet of green chemistry, green engineering, and industrial ecology, and since one of the greatest industrial wastes of our time is CO_2, it provides one of the greatest opportunities. Carbon dioxide can be utilized as a raw material in a wide range of applications, including the production of fuels, plastics and composites, and building materials.

Plastics and polymers have tremendous potential to sequester significant amounts of CO_2. Storing carbon in these materials results in valuable products that can be used in everything from infrastructure, to pipes, to packaging. The Yale Center for Natural Carbon Capture has funded several projects that explore new ways for industrial carbon utilization.

Industrial carbon utilization refers to the utilization of captured carbon dioxide from industrial processes rather than capturing and storing it via natural processes. Instead of solely storing the captured CO_2, industrial carbon utilization involves converting the captured carbon dioxide into valuable products or materials. The idea behind carbon utilization is to use carbon dioxide, promoting the circular economy, and reducing the net emissions from industrial processes in cases where the end products replace traditional carbon intensive materials.

There are several ways to utilize captured CO_2 in industrial applications. Some examples include using CO_2 as a feedstock for the production of chemicals, fuels, and building materials, such as concrete or plastics. By incorporating CO_2 into these products, carbon utilization helps to offset the need for fossil fuels and traditional carbon-intensive raw materials. Overall, industrial carbon utilization enhances the economic viability of carbon capture and storage projects by creating additional revenue streams from the CO_2 captured, while also contributing to the reduction of greenhouse gas emissions and advancing the transition to a more sustainable and low-carbon economy.

The Yale Center of Natural Carbon Capture is funding four major projects that investigate different aspect of industrial carbon utilization. Major advances of the last year include:

- Completing fundamental research for capturing carbon dioxide from dilute sources
- Significantly improving the efficiency of converting CO_2 to methanol, increasing the amount of methanol produced from 40% to 85%
- Developing and using specialized equipment like flow cells, high-pressure reactors, and membrane electrode assembly reactors to carry out the electrochemical reactions for converting CO_2 to CO and then to methanol
- Achieving an impressive energy efficiency improvement for synthesized catalysts which is 1.4 times better than previously known acidic CO_2 conversion systems; achieving a high efficiency of 57% in converting CO_2 to ethylene (C2H4)
- Designing and fabricating new reactors for activating CO_2

Funded Project: Capturing Carbon Dioxide from Dilute Sources for Chemical Catalysis

PI: Nilay Hazari, John Randolph Huffman Professor of Chemistry, Department of Chemistry

Researchers at Yale:

- Dr. Matthew Elsby, postdoctoral fellow, Department of Chemistry, Yale University
- Hailiang Wang, Professor, Department of Chemistry, Yale University

Collaborators at other institutions:

- Alissa Park, Lenfest Earth Institute Professor of Climate Change, Departments of Earth and Environmental Engineering & Chemical Engineering, at Columbia University

Project overview:

This project addresses the challenge of converting carbon dioxide (CO_2) into more valuable products, such as plastics or fuels, using dilute CO_2 streams commonly found in society, such as industrial flue sources. Currently, many CO_2 conversion systems are not efficient with dilute CO_2 streams, and traditional CO_2 capture technologies are expensive and energy intensive.

The project's goal is to develop a system that integrates CO_2 capture and conversion in a synergistic way to lower the energy costs associated with CO_2 conversion. The researchers focus on ionically conductive nanoparticle organic hybrid materials (NOHMs) that have a tunable polymer for CO_2 capture and functional groups to link with CO_2 conversion catalysts. These NOHMs can capture CO_2 from dilute gas sources and deliver higher local concentrations to catalytic sites for efficient conversion.

By designing and building such systems, the project aims to make CO_2 conversion more economically viable and practical for dilute CO_2 streams, contributing to the development of sustainable and efficient CO_2 utilization technologies.

First year progress:

The group has completed fundamental research that builds the foundation for the next applied phase of the project.

Scientific outputs:

The following manuscript was published:

1. Espinosa, M. R., et al. "Correlating Thermodynamic and Kinetic Hydricities of Rhenium Hydrides." J. Am. Chem. Soc., vol. 144, 2022, pp. 17939-17954.

Funded Project: Developing CO_2 Electrolyzers for Methanol Production

PI: Hailiang Wang, Professor of Chemistry, Department of Chemistry

Researchers at Yale:

- Seonjeong Cheon, postdoctoral associate, Department of Chemistry
- Chungsuk Choi, postdoctoral associate, Department of Chemistry

Collaborators at other institutions:

- Stafford Sheehan, Chief Technology Officer, Air Company

Project overview:

This project aims to develop a viable technology for electrochemical carbon dioxide (CO_2) reduction to methanol, a valuable chemical feedstock and liquid fuel. The researchers have already discovered a promising molecular electrocatalyst that can convert CO_2 to methanol with significant yield. Now, they seek to solidify the scientific foundation for this technology to outperform or complement natural processes. The 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. Through hypothesis-driven mechanistic studies and catalyst development, electrode design, and reactor engineering, the project aims to achieve these performance targets, bringing us closer to producing methanol from CO_2 with renewable electricity and advancing our understanding of catalytic science.

First year progress:

During the first year the group conducted detailed studies to understand how quickly carbon monoxide (CO) is formed during the conversion of CO_2 methanol. The researchers gained valuable insights into the specific processes involved in this CO formation, such as electron and proton transfers, and the overall reaction order. Research efforts also significantly improved the efficiency of converting CO_2 to methanol, increasing the amount of methanol produced from 40% to 85%. Finally, we developed and used specialized equipment like flow cells, high-pressure reactors, and membrane electrode assembly reactors to carry out the electrochemical reactions for converting CO_2 to CO and then to methanol. These advanced setups help better understand and optimize the process.

Scientific outputs:

We have initiated the process of filing a patent for the innovations stemming from this research.

Funded Project: Storing Carbon Dioxide in the Form of Sustainable Plastics

PI: Mingjiang Zhong, Assistant Professor of Chemical & Environmental Engineering and Chemistry, Yale School of Engineering & Applied Science

Researchers at Yale:

- Yinan Chen, PhD student
- Yazhen Xue, PhD candidate
- Junwoo Lee, postdoctoral researcher
- Taotao Gao, postdoctoral researcher

Collaborators at other institutions:

- Edward Sargent, Professor, Northwestern University and University of Toronto

Project overview:

This project aims to find efficient ways to capture and utilize carbon dioxide (CO_2) to create valuable materials, such as plastics, while reducing greenhouse gas emissions. The researchers are designing special catalysts that can turn CO_2 and natural compounds into strong and durable plastics. These plastics can be easily broken down and reused, creating a circular economy for plastics. Additionally, the project explores methods to directly transform CO_2 into the basic building blocks of materials, offering eco-friendly alternatives to high-emission production processes. In summary, this research provides a sustainable and beneficial strategy for reducing CO_2 levels and producing valuable materials.

First year progress:

During the first year the researchers were able to

- Create a collection of catalysts that can convert carbon dioxide (CO_2) and epoxide molecules into useful materials through a process called ring opening copolymerization (ROCOP)
- Design and make catalysts with special structures that have two active sites, making them highly efficient in the reaction under mild conditions
- Developed a method to convert CO_2 along with aromatic disulfide substances into valuable materials
- Synthesize catalysts that are stable in acidic conditions and can produce copper nanoparticles when exposed to strong acids. The synthesized catalysts showed impressive results, achieving a high efficiency of 57% in converting CO_2 to ethylene ($C2H4$). This significant improvement in energy efficiency is 1.4 times better than previously known acidic CO_2 conversion systems

Scientific outputs:

The research group developed several new methodologies and materials for converting carbon dioxide, which will be further explored for potential wide-scale applications.

Funded Project: Synergizing Lightning- and Photosynthesis-Inspired CO_2 Conversion Processes: Development of Plasma Electrolysis for CO_2 Activation and Selective Upgrading

PI: Lea Winter, Assistant Professor of Chemical and Environmental Engineering, Yale School of Engineering & Applied Science

Researchers at Yale:

- Ji-Yong Kim, postdoctoral associate
- Hailiang Wang, Associate Professor of Chemistry, Department of Chemistry

Project overview:

This project focuses on developing innovative technologies to convert carbon dioxide (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 reducing greenhouse gas emissions.

First year Progress:

In the first year of the project, the team made significant progress in combining plasma and electrocatalysis to convert CO_2 into valuable chemicals. Researchers designed and fabricated new reactors to efficiently activate CO_2 using plasma. They used copper as the initial catalyst material, and the combined plasma-electrochemical system showed promising results, producing a broader range of reaction products compared to electrocatalysis alone. The combined system demonstrated increased selectivity for various compounds, including methane, methanol, and C2 and C3 products, making it a promising approach for sustainable CO_2 conversion and utilization.

Scientific outputs:

The following manuscripts were published:

1. Butler, Claire, et al. "At-field and on-demand nitrogenous fertilizer synthesis." ACS Sustainable Chemistry & Engineering, vol. 11, no. 15, 2023, pp. 5803–5818.
2. Winter, Lea R., and Jingguang G. Chen. "Challenges and opportunities in plasma-activated reactions of CO_2 with light alkanes." Journal of Energy Chemistry, invited Future Article, in press.

Programs and Activities

Postdoc fellowship program

Attracting and supporting early career researchers that bring novel ideas and perspectives to Yale and the Center is a key mechanism for building future leadership in climate solutions. The Yale Center for Natural Carbon Capture has awarded three fellowships during the first recruitment round, and candidates are joining the Center this year. Their projects will expand the research portfolio of the Center and address a range of topics that further the Center's mission.

Kohen Bauer

Faculty Advisors: Matt Eisaman and Noah Planavsky

Academic Unit: Department of Earth and Planetary Sciences

Focus area: Geological and Ocean Capture

Planned research project: Measurement, Reporting, and Verification of Ocean Alkalinity Enhancement

What is the project about?

Kohen Bauer's project will use ocean models to explore key aspects involved in the Measurement, Reporting, and Verification of the CO_2 removed as a result of ocean alkalinity enhancement interventions. Specifically, Kohen will: (1) Assess the fraction of removed CO_2 that can be verified by direct measurement given the accuracy and precision of current carbonate chemistry sensors; (2) Design alkalinity release strategies that maximize this directly detectable fraction; (3) Design sensor networks (sensor type and location) that maximize this directly detectable fraction; and (4) Quantify targets for sensor improvement that would significantly increase the fraction of removed CO_2 that can be directly detected. These results may be validated by measurements at an operating ocean alkalinity enhancement site if access to such a site is possible.

How does it expand the Center's research agenda and relate to existing Center research:

This project is strongly connected to existing research at the Center on ocean-based carbon dioxide removal but expands the Center's research agenda by providing more depth on the specific issue of Measurement, Reporting, and Verification for ocean alkalinity enhancement.

Broader impact:

Ocean alkalinity enhancement has the potential to remove gigatons of carbon dioxide form the atmosphere over the coming decades. However, reducing uncertainty in the measurement and verification of the amount of removed CO_2 is critical to the scaling of this technology by providing greater confidence to the carbon dioxide removal markets.

Spencer Moeller

Faculty Advisor: Ruth Blake

Academic Unit: Department of Earth and Planetary Sciences

Focus area: Geological and Soil Capture

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?

The proposed project will investigate an important potential co-benefit of enhanced rock weathering on agricultural fields. The type of rock most often used for enhanced weathering applications, basalt, also contains phosphate, a nutrient that is crucial for plant growth (as well as all living organisms). Farmers usually use phosphate fertilizers to enhance crop yields, which in turn can require additional resources and cause emissions along the production and application. This project will investigate whether adding ground up basalt to fields enables the plants to take up phosphate from that basalt and therefore reduce the need for phosphate fertilizer application.

How does it expand the Center's research agenda and relate to existing Center research:

This project directly relates to ongoing research on enhanced rock weathering and will investigate potential co-benefits of applying ground basalt to agricultural fields.

Broader impact:

Applying fertilizer to agricultural fields is a major source of cost, labor input, and emissions. Potentially reducing the need for fertilizer application will directly impact the willingness of farmers to apply this method on their land.

Fan Yang *(Dr. Yang will be the Center's inaugural industrial fellow, fostering interaction with industry partners)*

Faculty Advisor: Yuan Yao

Academic Unit: Yale School of the Environment

Focus area: Industrial Carbon Utilization.

Planned research project: Decarbonizing the Aviation Sector by Carbon Capture and Utilization

What is the project about?

The goal of the proposed project is to explore the potential impact of carbon capture, utilization, and storage in alternative aviation fuels in the context of climate change mitigation over time. This project will address three questions: (1) What are the climate change mitigation potential and other environmental impacts of carbon capture, utilization and storage combined with different sustainable aviation fuel production pathways? (2) What is the techno-economic performance of different combinations of carbon capture, utilization and storage and sustainable aviation fuel production systems, and how to optimize the synergies from both environmental and economic impacts? (3) What are economically feasible pathways to decarbonize the aviation sector in the United States taking the spatial distribution of natural resources, CO_2 point sources, and CO_2 storage sites into consideration?

How does it expand the Center's research agenda and relate to existing Center research:

This project directly relates to ongoing research funded by the Yale Center for Natural Carbon Capture and will expand and draw from existing expertise on life cycle assessment (LCA) and techno-economic models of the research group led by Yuan Yao. Furthermore, this project will support the collaboration between the Center, the research group, and the aviation industry.

Broader impact:

This research will inform decision making in policy (e.g., U.S. low carbon fuel standards) and the U.S. aviation industry by providing a better understanding of potential co-benefits and trade-offs of synergizing carbon capture, utilization and storage and sustainable aviation fuel production from both economic and environmental perspectives.

Workshop Program:

The workshop program at the Yale Center for Natural Carbon Capture is one of the many tools that the Center provides for the Yale community to connect to and collaborate with researchers from around the world. This is one of several ways in which the Center leverages Yale's reputation and convening power. In 2023, the directors selected six workshops for funding on the following topics:

Understanding Natural Biogenic Methane Fluxes from Ecosystems (Malone, YSE)

Summary:

This workshop will gather a community of experts to develop a vision for a continental methane observatory. Scientists with expertise in biogenic methane cycling will convene at Yale to discuss ways to design, construct, and operate the observatory. The main objectives of the workshop are to: (1) understand researcher needs for quantifying biogenic methane fluxes, (2) identify physical and cyber-infrastructure components that would address those needs, (3) determine the data products and use cases that would best serve scientists and other stakeholders in constraining biogenic contributions to the global methane budget, (4) identify innovative training opportunities that the continental methane observatory could offer, and (5) devise pathways for continued engagement with the research community in the establishment of the continental methane observatory. The workshop will result in a white paper and will also be used to record community support for a midscale infrastructure proposal to the National Science Foundation.

Number of invited participants: 37; (17 from academia, 10 from government agencies, 9 from NGOs or non-university research institutions; 1 Private Sector)

The Role of Tropical Crops in Natural Carbon Capture: The Case of Coffee (Hernandez-Aguilera, YSE)

Summary:

The objectives of this workshop are (1) to exchange, discuss, and synthesize ideas for models of coffee production and trade that could contribute to natural carbon capture and that can be part of insetting and offsetting carbon mitigation schemes, (2) exchange ideas about the technical aspects of mapping and measuring, valuing, and trading sequestered carbon in coffee landscapes, (3) investigate and discuss how companies at different sectors of the coffee industry––commodity coffees, specialty coffees––are planning to comply with new regulations to reduce deforestation and carbon emissions in the coffee supply chain, (4) discuss the enabling conditions (i.e., sociopolitical, institutional and technical contexts) that would be required for making natural carbon capture in coffee landscapes a working reality. The workshop will produce a white paper that will lead to scientific and general audience publications.

Number of invited participants: 14 (5 university; 4 research institutes; 5 practitioners)

Increasing Consensus on Best Practices in Establishing and Calculating Baselines for Forest Carbon Credits (Kuebbing, YSE)

Summary:

The purpose of this workshop is to convene experts in a diversity of disciplines and expertise to outline a rigorous list of best practices for estimating baselines for forest carbon crediting programs.

Number of invited participants: 43; (17 from Yale, 11 External researchers; 9 Standard Developers; 6 Project Developers & Carbon Project Consultants)

Capturing Carbon in Tropical Forests: Unraveling the Productivity-Mortality Paradox To Maximize Carbon Sequestration (Wong, EEB)

Summary:

This workshop will bring together leading tropical forest researchers to present their perspectives on the topic, compile a modern list of hypotheses that could explain the mortality-productivity paradox, identify data that could be used to test the hypotheses, and write a larger implementation proposal and perspective to outline early findings.

Number of invited participants: 33; (all from universities and research institutes)

Outreach and Engagement

Corporate engagement and roundtable meetings

November 2022

- The Fall meeting of Corporate Partners was held at FedEx's corporate headquarters in Memphis, TN. The visit included a dinner hosted by FedEx and guests from the Center, Boeing, and Southwest Airlines. The meeting included a presentation on Yale Ventures from Josh Geballe, Senior Associate Provost for Entrepreneurship & Innovation, a research updates session from Liza Comita, and a roundtable discussion moderated by Dean Indy Burke.

May 2023

- The Center hosted a corporate meeting which included presentations from three of the new YCNCC-endowed faculty members on their research on carbon sequestration and storage in soil, tropic forests, and ocean ecosystems. Leadership from Boeing, FedEx, and Southwest Airlines presented updates about their sustainability plans. The first two research briefings on enhanced mineral weathering and the Yale Applied Science Synthesis Program were delivered to the corporate partners.

March 2023

- Climate Solutions Conversation (Liza Comita and Frances Seymor), an educational webinar for sustainability professionals from FedEx, Southwest, and Boeing. Center Co-Director Liza Comita presented on tropical forest carbon storage alongside a colleague from the World Resources Institute. The webinar was attended by 90 guests.

Industry Fellowship

- In response to conversations with corporate partners, the YCNCC initiated the "Industry Fellowship", which will be a term-limited (rotating) program for a postdoctoral or research scientist who can participate in non-proprietary collaboration and engagement with corporate donors and industry leaders. The first candidate for this position has been filled and will start their appointment on January 1st, 2024. They will address the gap in understanding the greenhouse gas mitigation potential and economic feasibility of diverse sustainable aviation fuel and carbon capture, utilization and storage pathways and their synergies.

General Outreach and Engagement Activities

October 2022

- Liza Comita, Sparkle Malone, and Jim Saiers participated in a panel on Natural Carbon Capture research at the Yale School of the Environment Reunion Weekend. They provided an overview of the Center's work, diving into Professor Malone's research on the capacity of natural and managed ecosystems to sequester carbon and Professor Saiers' work on field trials to test enhanced rock weathering.
- Dave Bercovici and Liza Comita provided a lecture on the carbon cycle and the science of climate change and an overview of the work being done by the Center to the cohort Yale Emerging Climate Leaders Fellows; a group of 16 international fellows from the global south.

November 2022

- Dave Bercovici gave a World Scholars Cup Lecture on Climate, Carbon, and Carbon Capture at the Schubert Theater in New Haven, CT. The audience consisted of approximately 400 high school students.
- Sara Kuebbing, Mark Bradford, Reid Lewis, Will Gardner provided commentary on the proposed guidance on how companies should account for and report greenhouse gas emissions and removals from land management, land use change, carbon dioxide removal technologies, and related activities in greenhouse gas inventories for the Greenhouse Gas Protocol Land Sector and Removals Guidance (Corporate Standard and Scope 3 Standard) Draft Protocol Request for Comment.
- Sara Kuebbing, Mark Bradford, Joe Orefice, Mark Ashton, and Marlyse Duguid provided information on how the US Forest Service and Land Management Bureau should develop definitions of "old-growth" and "mature forests" and assess the extent of these forest types on federal forest lands to the US Forest Service and Land Management Bureau Request for Information on Federal Old-growth and Mature Forests.

December 2022

- Sara Kuebbing participated in a Plenary Panel, "Forest Ecosystem Monitoring Cooperative Conference Advances in Forest Science: The Role of Emerging Technology in Forest Science, Ecosystem Stewardship and Stakeholder Engagement" at University of Vermont, Burlington, VT.
- Cole Gross, Sara Kuebbing provided advice to letter author lead of the Ocean Spray Cranberry, Inc. sustainability team on key publications and scientific knowledge around cranberry farming and carbon benefits for the Natural Resource Conservation Service Request for Public Input About Implementation of the Inflation Reduction Act Funding.

January 2023

- Laura Toro contributed to the Restoration Scoping Dialogue hosted by The Forest Dialogue, Yale University. She presented on The Role of the Forest Sector during the UN Decade on Ecosystem Restoration.

- Sara Kuebbing, Mark Bradford and Lisa Eash attended the Row Crop Greenhouse Gas Mitigation Research Workshop hosted by Environmental Defense Fund, Washington, DC, USA to identify research opportunities and data gaps for improving soil carbon estimates for the voluntary carbon market.

February 2023

- Laura Toro moderated a Panel on "Building Partnerships for Forest Restoration" and was a participant in the "Fantastic restoration monitoring tools and where to find them" roundtable session at the International Society of Tropical Foresters Annual Conference "Envisioning the Future of Tropical Forests" hosted by Yale University.
- Cole Gross and Sara Kuebbing presented at the 2023 Carbon Storage and Cycling in Cranberry Farm Ecosystems. Ocean Spray Cranberry, Inc. Annual Grower's Meeting in Nashville, Tennessee. Two separate presentations in two independent sessions at the meeting, each attended by ~100 cranberry farmers, addressed carbon stocks in cranberry ecosystems.

March 2023

- Liza Comita & Dave Bercovici provided an overview of the Yale Center for Natural Carbon Capture to development officers at Yale as part of the Office of Development's Science Snapshot Workshop Series to help ensure that they are aware of the Center's work and can steer potential donors interested in climate change solutions to the Center.

April 2023

- Sara Kuebbing served as Australian Associated Press FactCheck expert, cited in their article "Carbon emissions claim is barking up the wrong tree" Williams D. 2023. Carbon emissions claim is barking up the wrong tree. AAP FactCheck. Link: https://www.aap.com.au/factcheck/carbon-emissions-claim-is-barking-up-the-wrong-tree/.

May 2023

- Sara Kuebbing Moderated a panel with Jeff Briggs (New Forests) and Gabe Sheets-Poling (Ripple) at the Conservation Finance Annual Conference. Panel Debate: Carbon markets & carbon reality: how to scale nature-based solutions while maintaining market integrity. The conference was held at Credit Suisse, New York, New York.
- Congressman Bruce Westerman (YSE '01 MF) of Arkansas, current chair of the House Committee on Natural Resources, brought committee members to visit Yale to learn about sustainable forest management. A total of over 20 Congresspeople and committee and agency staff were in attendance. Center co-director Liza Comita provided the delegation with an overview of the work of the Center. The delegation also heard presentations on projects by Center-affiliated faculty on research related to forests, carbon storage, and climate. The delegation then took a field trip to Yale Myers Forest to see sustainable forest management practices in action. Attendees included: House Committee on Natural Resources Chairman Bruce Westerman (R-Ark.) and U.S.

Reps. John Curtis (R-Utah), Doug LaMalfa (R-Calif.), Val Hoyle (D-Ore.), Ed Case (D-Hawaii), Pete Stauber (R-Minn.), Mike Collins (R-Ga.), Mariannette Miller-Meeks (R-Iowa), Melanie Stansbury (D-N.M.), Amata Radewagen (R-American Samoa) and Jim Moylan (R-Guam).

- Dave Bercovici presented at the Yale Alumni reunion addressing details about natural carbon capture and the explaining the work the Yale Center for Natural Carbon Capture.
- Spring Symposium on Enhanced Rock Weathering: The Yale Center for Natural Carbon Capture welcomed corporate partners from FedEx, Southwest Airlines, and Boeing to campus. (Please see section "Events at Yale" for details on symposium speakers and outcomes).

June 2023

- Dave Bercovici presented at the Yale Alumni reunion addressing details about natural carbon capture and the explaining the work the Yale Center for Natural Carbon Capture.
- Sara Kuebbing moderated a panel with Travis Croft (The Climate Trust), Nathan Truitt (American Forest Foundation), and Liz Johnston (City Forest Credits) at the Conservation Finance Boot Camp.
- Lisa Eash and Anna Stemberger attended The Indigo Science & Policy Forum hosted by Indigo Ag in Boston, MA, USA for networking with soil agricultural carbon market credit developers and parties interested in high-quality agriculture carbon credits.
- Sara Kuebbing attended the Forestry R&D Priorities Summit on June 6-8, 2023. Hosted by Society for American Foresters, Washington, DC, USA. The goal of the event was to Build a coalition of forest research and development organizations to effectively communicate the importance of forest research to funding agencies and the public.
- Laura Toro attended the Field Dialogue: Tree plantations in the Landscape hosted by The Forest Dialogue in Indonesia to discuss how tree plantations in southeast Asia fit within climate mitigation framing.
- Mark Bradford, Sara Kuebbing (and others including researchers from EDF, Carbon180, NRDC, Soil Health Institute, Science Societies, Yardstick) provided suggestions for USDA soil sampling and measurement procedures for monitoring soil carbon changes in response to agricultural management for the US Department of Agriculture Conservation Evaluation and Monitoring Activity (CEMA) Soil Organic Carbon Stock Monitoring Protocol Request for Comments. June 2023.

Ongoing:

- Sara Kuebbing and Mark Bradford attended the NASA Harvest Sustainable and Regenerative Agriculture (SARA) Model Evaluation Working Group. Going forward they will provide expert advice on evaluating different soil carbon biogeochemical models for carbon projections in agricultural landscapes.
- Kuebbing moderated a special Yale Forest Forum webinar on Russia's War and Ukraine's Forests: Destruction and Resilience with experts Brian Milkovsky (Consultant) and Sergiy Zibtsev (Professor, Department of Silviculture, National University of Life and Environmental Sciences of Ukraine) about how war and climate change are impacting Ukraine's forests, including implications for carbon emissions from wildfires and inability to manage. Kuebbing is working with Mikovsky and Zibtsev on a Special Issue on the topic, pitching to Forest Ecology & Management.
- Kuebbing and Liu have held a series of meetings in 2022 with regional northeastern foresters that manage and measure commercial forestlands and state and municipal forests. These meetings have developed into a loose network of connections between Yale Applied Science Synthesis Program and regional forest managers, and have led to data sharing, better understanding of regional forest management needs and issues.
- Greame Berlyn and Anithra Thoraug are working with the Sri Lanka Foreign Affairs Office for Oceans and Climate Change on collaborating directly with United Nations agencies for Blue Carbon Enhancement in Sri Lanka (IPCC, FAO, UNEP, UNDP). This effort is ongoing from June 2023-fall 2024.

Environmental Leadership and Training Initiative (ELTI)

The Yale Center for Natural Carbon Capture (YCNCC) works with Yale's Environmental Leadership & Training Initiative (ELTI) to develop educational materials and provide training opportunities focused on natural carbon capture and carbon markets for practitioners, decision makers, and corporate audiences. Since 2006, the ELTI team has developed an array of field and online training opportunities for over 5,000 people who are implementing conservation and restoration interventions in tropical forest landscapes. As an initiative of Yale's School of the Environment, the ELTI team works with YSE faculty and a network of global partners and experts to design and implement the program's field and online activities. Over the past year, the ELTI team continued to progress with developing an array of educational materials and training opportunities that directly contribute to the Center's mission. They also secured funding to launch the inaugural cohort of Three Cairns Fellows who focus on climate change mitigation in the Global South.

Educational materials:

- New video lecture, case study, and interview focused on climate change and carbon markets completed for ELTI's yearlong Tropical Forest Landscapes (TFL) online certificate program. The ELTI team has trained 340 participants from 69 countries via four cohorts of the TFL certificate, which focuses on people in government, NGOs, donor organizations, the private sector, and academia who are designing and implementing projects. These three new contributions, combined with the two recorded lectures developed last year by David Bercovici and Frances Seymour, are part of ELTI's expanding curriculum on climate change and carbon markets. The ELTI team will continue to develop related educational materials to include in the TFL certificate and an array of other courses and events:

    - Lecture: The Amazon Basin in transition: implications and opportunities for nature-based solutions **–** Paulo Brando, Ph.D., YCNCC faculty: This video lecture is one of the foundational presentations for the module on climate change mitigation and adaptation in the 8-week Strategies course of the TFL certificate. Dr. Brando reviews deforestation patterns and trends in the Amazon region, the effects of these trends on water and biomass, and the complexity of climate change and fire on this unique ecosystem.

    - Case Study: The LEAF Coalition: A jurisdictional approach to reduce reforestation through voluntary carbon markets – Eron Bloomgarden, CEO of Emergent, and Rocio Sanz Cortes, Executive VP, Origination: This case study is featured in the 8-week Funding course of the TFL certificate. The presenters introduce the LEAF coalition and how it works, the jurisdictional approach to REDD+, and how benefits are shared, including a case study from Costa Rica (a member of the World Bank's Forest Carbon Partnership Fund).

    - Interview: Role of private project developers in forest carbon markets – Hassan Sachedina, Ph.D.; CEO and Co-founder of Sayari Earth and former CEO of BioCarbon: In this interview, Professor Brad Gentry of YSE discussed the experiences of Dr. Hassan Sachedina with BioCarbon Partners (BCP), one of the world's largest and most impactful REDD+ developers in terms of scale and number of people impacted.

- The ELTI team also worked this fiscal year with YSE Professor Peter Raymond and graduate student Frannie Adams (MESc ’23) to develop a new lecture on the contributions of mangrove forests to climate change mitigation for ELTI’s TFL online certificate curriculum. They will complete the lecture in time for the ELTI team to include it in the 8-week Fundamentals course during the next certificate cohort (June 2023-May 2024).

Training opportunities:

- New online course and webinar presentations implemented by ELTI team members and alumni focused on carbon markets and climate-smart ranching:
  - Online course: Introduction to carbon markets – implemented in Portuguese for Brazilian practitioners by ELTI’s field-based affiliates Maria Otávia Crepaldi, Ph.D., and Erica Munaro. Maria Otávia and Erica are employees of ELTI’s partner organization in Brazil – IPÊ, Brazil’s Institute for Ecological Research – and are based in the IPÊ-ELTI’s training landscape in S. Bahia. They designed the course to provide forest restoration practitioners in the region with introductory content on carbon measurement and markets, so they are better prepared to participate in emerging sustainable production projects.
  - Webinar presentations focused on carbon markets – delivered by four ELTI alumni during two webinars held during March 2023 (English and Spanish)
- New online courses, one focused on carbon markets and the other on mangroves, under development by ELTI team members, in collaboration with YSE faculty and collaborators:
  - Online course: Carbon markets for the buyers of carbon credits continued to progress with the launch of a search for a consultant to lead the development of the course curriculum. The consultant will draw upon the outcomes of the market analysis and two YSE webinar series on carbon markets implemented during the fall ’22 and spring ’23 semesters to develop an online short course for a global audience (summer of 2024).
  - Online course: Remote sensing for carbon in mangrove ecosystems is a potential new initiative led by YSE Professor Pete Raymond & his colleagues at NASA. The ELTI team had several initial exploratory meetings with Professor Raymond and his NASA colleagues and will continue discussing potential opportunities in the coming months.

Yale Forest Forum

YCNCC researcher, Dr. Sara Kuebbing, served as an advisor to the Yale Forest Forum in fall 2022 (Title: What Makes a High-Quality Forest Carbon Credit?) and spring 2023 (Title: How Can the Voluntary Carbon Market Make a Meaningful Contribution to Protecting Tropical Forests?). The Yale Forest Forum is part of the Forest School at the Yale School of the Environment. It serves as a forum for engagement, learning, and collaboration on topics related to forests and forest landscapes. The lectures include speakers come from a wide range of organizations and perspectives, including government, Indigenous peoples and local communities, NGOs and businesses, working at scales from the local to international.

Lectures are open to the public, available online (both live and recorded), and frequently attract audiences of hundreds of people from across the world.

Communications Strategy

With the Center's scientific operations now fully underway, we are now working to craft a robust communications strategy. Our main communication goals are to enhance research collaborations, disseminate our research findings to relevant audiences both within and outside of academia, communicate the role of natural carbon capture in climate mitigation to the greater public, and to serve as global leaders in catalyzing novel climate solutions. To drive this initiative, we are in the process of hiring a dedicated Communications Director who will head these efforts. As our scientific endeavors thrive, this dedicated effort towards a comprehensive communication strategy will ensure the Center has a broader impact and makes meaningful contributions to tackling ongoing climate issues. In our strategy, we consider the following:

Purpose

As a Center at an academic institution, we recognize two different purposes for communication and outreach:

Promotion, to elevate the Center’s profile across sectors, attract talent, and establish the Center and its scientists as authorities and resources for questions related to natural carbon capture.

Problem solving, to contribute to key discussions and provide up-to-date scientific information for application of nature-based climate solutions.

Audience

The first audience for scientific research results is usually the scientific community. However, for successfully implementing the Center mission of supporting climate change mitigation, the information generated by the Center needs to reach decision makers, practitioners, and other stakeholders on various levels.

Content

Along with research results and general Center news, the Center will provide overviews of the state of the science for relevant topics, information about how a solution can be implemented, and potential pathways to implementation.

Plans for the coming year:

Along with a major upgrade of the Yale Sites platform, which currently hosts the Yale Center for Natural Carbon Capture website, the Center website will be redesigned to better meet the Center’s needs for communication and outreach. This will be done by working with Yale internal designers and programmers, or through an external agency.

As research results are published and are available to the public, the Center will create impact statements for individual publications that explain in non-technical terms what the published research is about and how it contributes to solving the climate crisis.

Starting with the fall semester of 2023, a regular newsletter announcing events, activities, opportunities will be shared through the Center email list and with departments and schools across Yale.

Additionally, once a year following the completion of the annual stewardship report, a shorter public version of the report will be compiled to serve as a newsletter, which will be shared with the wider Center community and external partners.

In addition to written communications (e.g., research briefs, scientific publications, and reports), the Center uses workshops, symposia, courses, and webinars as outreach and problem-solving tools.

Events at Yale University

The Yale Center for Natural Carbon Capture hosts, sponsors and organizes a number of events on campus each year. Most events fall into one of three categories: a) co-hosted or sponsored speaker events as part of departmental speaker series, b) Center organized events to advance the mission and strategic plan of the Center such as the annual spring symposium, and c) events to facilitate networking for scientists of different departments.

Spring Symposium: Enhanced Rock Weathering

May 01 – May 02, 2023

The main event organized and hosted by the Yale Center for Natural Carbon Capture is the annual Spring Symposium. This year's event focused on Enhanced Rock Weathering and brought together leading experts from around the world and from sectors spanning academia, nonprofit organizations, and the private sector. With this, the symposium provided a space and time for facilitating discussion and collaboration between speakers and the audience.

The symposium schedule included introductory lectures and panel discussions with ample time for questions from the audience. Each session was followed by a period for socializing and continuing discussions. By convening this group of leading experts, the Center enabled critical discussion, networking, and new collaborations between sectors and actors. The event was divided into five sessions and provided plenty of time for discussion among speakers and participants.

Monday May 1st:

Keynote talks:

Holly Jean Buck, Assistant Professor, Department of Environment and Sustainability, University at Buffalo

David Beerling, Sorby Professor of Natural Sciences, School of Biosciences, University of Sheffield

Tuesday May 2nd:

Panel 1: Scientific Unknowns (Salvatore Calabrese, Jim Saiers, Becca Neumann, David Beerling; Moderated by Pete Raymond)

Panel 2: Monitoring, Reporting, Verification & Governance (Maya Almaraz, Justin Richardson, Dimitar Epihov, Stephanie Grand; Moderated by Anu Khan)

Panel 3: Co-benefits & Societal Impacts (Rachael James, Freya Chay, Tom Reershemius, Elizabeth Troein; moderated by Chris Reinhard)

Panel 4: Commercialization & Marketplaces (Anu Kahn, Grace Andrews, Mary Yarp, Adam Wolf; Moderated by Noah Planavsky)

Other Events at Yale

September 28th, 2022

- Biomes Seminar: 'Tropical Forests: The Cinderella of Solutions to Climate Change' by Frances Seymor, Distinguished Senior Fellow, World Resources Institute, McClusky Fellow, Yale School of the Environment

September 30th, 2022

- Yale Center for Natural Carbon Capture: Early career researchers meeting convening postdoctoral researchers and PhD students for an informal introduction to the work of the Center, opportunities for researchers, and introduction of each other's research projects.

October 12th,2022

- Yale Center for Natural Carbon Capture Fall Fest: Gathering for Center affiliated researchers and staff, this was the first opportunity for all Center affiliated members of the Yale community to come together, get to know each other and learn about each other's research or role within the Center.

October 14th, 2022

- Global Environmental Justice Conference: sponsored a panel discussion on 'Nature-Based Climate Solutions and Indigenous Rights' with Silvia Gómez, Executive Director of the Gaia Amazonas Foundation and Professor of Sociology and International Relations, La Universidad San Francisco de Quito

December 7th, 2022

- Postdoc Seminar: 'Soil structure formation during landscape and agricultural reclamation' Evilin Philap, Postdoctoral fellow at Yale Department of Earth and Planetary Sciences

March 3rd, 2023

- Yale Center for Natural Carbon Capture Faculty retreat: This half day event brought together over 30 faculty, researchers, and staff from across the University to identify knowledge gaps in their respective fields of expertise, provide insights into how the Center can have the most impact and share approaches for communicating scientific results and information to specific audiences.

April 4th, 2023

- Biomes Seminar: 'What Can Economists Contribute to Climate Policy?' by Catherine Wolfram Visiting Raymond Plank Professor, Harvard Kennedy School

April 25th,2023

- Chemistry Seminar: 'Solar Panels for Light to Chemical Conversion' by Erwin Reisner, Professor of Energy Sustainability, Department of Chemistry, Cambridge University

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.

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 for various decision-making processes such as postdoctoral fellowship awards and research awards
- Ensure accessibility of Center events by providing special accommodation when needed, such as various ways to participate (remote and in person), respecting boundaries of work non worktimes whenever possible to enable caregivers to participate as much as possible, actively inquire about and tend to any other specific needs such as dietary restrictions, transportation needs and more.
- Actively diversify how the Center advertises opportunities such as fellowship positions to reach underrepresented demographics
- Sponsoring a session at the Global Environmental Justice Conference addressing the effect of climate solutions on indigenous peoples
- Select speakers and panelists to represent diverse perspectives, based on geographic or ethnic origin, sector or field of expertise, or career stage
- Provide funding to the Environmental Training and Leadership Initiative, which directly works with practitioners implementing nature-based climate solutions
- Require commitment to implementing 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 of 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 Hunt

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
Sue Armatudo

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
Anna Schuerkmann

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.

Assistant Director for Communications
New Position, part time with YCNCC

The assistant director for communications implements the Center's communications plan

Student Assistants
Wen Rui Tai
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

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

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 Ashton
Senior Associate Dean of The Forest School; Professor of Silviculture and Forest Ecology; Director of Yale Forests, Yale School of the Environment

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

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

Matt Eisaman
Associate Professor, Department of Earth and Planetary Sciences

Nialy Hazari
Professor of Chemistry, Department of Chemistry

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

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

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

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

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

Julie Zimmerman
Senior Associate Dean of Academic Affairs, Professor of Green Engineering, Assistant Director for Research at Center for Green Chemistry and Green Engineering, Yale School of the Environment

Conclusion

The Yale Center for Natural Carbon Capture has successfully completed its ramp up phase, hired four new faculty, and established a variety of research programs and regular activities. Center leadership is establishing mechanisms to support key initiatives in their next phase of research on implementation and up-scaling, as well as a robust measurement, reporting and verification framework.

Given the establishment of a stream of scientific progress and content, the Center will expand its communications program for creating impactful outreach and educational materials with which to enable decisionmakers on all levels to implement solutions based on the most up to date science.

Additionally, the Center will grow its efforts in the field of industrial carbon utilization by hiring a fifth faculty member in the Yale School of Engineering and Applied Sciences.

Altogether, the generous gifts from the FedEx Corporation, Southwest Airlines, and the Boeing Company are making an unprecedented contribution to developing natural carbon capture solutions.

We are excited about supporting our researchers' passion and unique combination of skills and expertise into the next phase and establishing direct lines of communication from innovative research to decision makers and practitioners.