Investigating Enhanced Mineral Weathering in Australian Blue Carbon Ecosystems as a Method of Carbon Dioxide Removal

James Westphalen

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Started the Environmental Science PhD program in Fall 2023

**Adviser:** Dr. Tyler Cyronak

**Thesis Title:** Investigating Enhanced Mineral Weathering in *Spartina* Dominated Salt Marshes as a method of Carbon Dioxide Removal

**Exchange Site:** Southern Cross University Centre for Coastal Biogeochemistry, Lismore, Australia

**Collaborator:** Dr. Bradley Eyre
Abstract

Developing methods for atmospheric carbon dioxide removal (CDR) is essential for keeping global warming within the climate goals set by the Intergovernmental Panel on Climate Change (IPCC). Enhanced mineral weathering (EMW), or the mechanical breakdown of alkaline rocks to speed their reaction with carbon dioxide, is an effective strategy currently being applied to terrestrial ecosystems and agricultural fields. Despite the abundance of research on enhanced weathering in terrestrial ecosystems, there is less known about this CDR strategy in marine systems. Coastal and estuarine ecosystems may offer important benefits to mineral weathering due to conditions that could facilitate faster weathering and dissolution of the ground rock. This project will build off my PhD research by investigating methods of EMW in blue carbon ecosystems of Australia through a collaboration with the Southern Cross University Centre for Coastal Biogeochemistry. During my time in Australia, I will investigate the carbon removal capabilities of combining the EMW of olivine and basalt with blue carbon ecosystems such as marshes and mangroves through in situ chamber work combined with porewater chemistry. I will conduct short term (24-hr) incubations of sediment that is amended with alkaline rock material and compare carbon fluxes to undisturbed areas. The Centre for Coastal Biogeochemistry is an ideal location to conduct this study because of the instrumentation and resources that are available, access to diverse blue carbon ecosystems, and collaborations with PhD students, postdoctoral fellows and academics that are based at this institution. Acceptance to this exchange program will allow me to investigate methods of enhanced weathering in additional locations and ecosystems beyond what I have planned for during my research in Georgia’s saltmarshes. It will also improve my career by giving me access to state-of-the-art biogeochemical research tools and instrumentation and increase network opportunities within my field.

Key words: carbon dioxide removal, blue carbon, enhanced weathering, ocean alkalinity enhancement, coastal ecosystems
Project Description

Blue carbon ecosystems, such as salt marshes, mangrove forests and seagrass meadows, sequester and store carbon through living biomass, the burial of carbon in sediment, and the export of alkalinity. Carbon sequestration within blue carbon ecosystems could be artificially increased through the addition of ground silicate rock, which will dissolve and release alkalinity to the surrounding waters. Ocean alkalinity enhancement is a promising carbon dioxide removal (CDR) technology that results in the drawdown of atmospheric carbon dioxide and long-term storage as dissolved inorganic carbon in seawater. The enhanced weathering of silicate rocks not only releases alkalinity but can slowly leach trace minerals that enhance the growth of plants. How these processes will interact within natural blue carbon ecosystems to increase carbon capture is unclear. However, there are potential co-benefits for implementing enhanced weathering in coastal ecosystems. The applicability of enhanced weathering in blue carbon ecosystems may be useful as these ecosystems already transport carbon to the ocean and provide dynamic conditions that will allow for more efficient weathering of the ground rock. With acceptance to the LOREX fellowship, I will be able to investigate the effectiveness of enhanced mineral weathering (EMW) methods as carbon dioxide removal technology in blue carbon ecosystems in Australia. While based on the Georgia coastal plain with Georgia Southern University, I have access to North American salt marshes for this research. However, with acceptance to the LOREX fellowship, I would also have the opportunity to apply methods of EMW to blue carbon ecosystems in New South Wales. I will investigate the effectiveness of EMW methods in mangrove ecosystems, marsh ecosystems and coastal marine ecosystems in Australia.

Background

Development of this project is based on the current need for the development of CDR technologies to mitigate anthropogenic climate change according to the IPCC (IPCC, 2021). Climate change is responsible for disruptions in the Earth system, including global warming, changes in weather patterns, ocean acidification, and sea level rise (IPCC, 2021). Human perturbations to the global carbon cycle are the main cause of modern climate change, which is largely driven by the buildup of fossil fuel derived greenhouse gases in the atmosphere (Mikaylov et al. 2020). Greenhouse gases induce a warming effect by trapping longwave radiation and emitting it back to the Earth’s surface and atmosphere. The major driver of modern climate change is carbon dioxide (CO₂), which has a long residence time in the atmosphere (>500 years) (Archer 2005). Other significant greenhouse gases include methane (CH₄) and nitrous oxide (N₂O). Both CH₄ and N₂O have higher warming potentials than CO₂ but have shorter residence times due to destructive chemical reactions that occur in the atmosphere (Boucher et al. 2009, Fuglestvedt et al. 1996). Over time scales less than 100 years, CH₄ has a global warming potential 27 times that of CO₂ (Boucher et al. 2009), and is produced anthropogenically by livestock, agriculture, and landfills. In total, the sum of all anthropogenic greenhouse gas emissions has led to a global warming of 1.07°C over the past century, and the trend is expected to continue depending on future emission scenarios (IPCC 2021).

Marine and coastal ecosystems that sequester carbon are known as blue carbon ecosystems. Blue carbon ecosystems are effective at carbon sequestration and can be up to 40% more productive than terrestrial ecosystems such as rainforests (Duarte et al. 2005). These ecosystems include mangrove swamps, seagrass meadows, macroalgae forests and salt marshes. Much of the carbon in these ecosystems is stored internally by the accumulation within living biomass and burial in
soils and sediments (Filbee-Dexter & Wernberg 2020), while some is stored as dissolved inorganic carbon that is transported to the open ocean (Wang et al. 2016, Yau et al. 2022). Carbon that is transported to the open ocean in the form of bicarbonate or carbonate ions can be sequestered for long time scales (>10,000 years).

CO$_2$ can also be stored by geological processes such as mineral weathering. In this process, CO$_2$ and water are consumed in the chemical breakdown of minerals, and dissolved inorganic carbon is produced, mainly in the form of bicarbonate, and carbonate to a lesser extent. This process is thought to regulate CO$_2$ concentrations in the Earth’s atmosphere over millions of years (Beerling et al. 2018). Dissolved inorganic carbon that is produced by the weathering of silicate rocks can be stored in the ocean for long time scales given it does not precipitate back into sediments in a reversal of the weathering process. This process has been utilized as a form of artificial carbon storage in EMW (Haque et al. 2023). Although EMW has only been commercially implemented in agriculture so far, there is ongoing research into whether this process can be used effectively in coastal ecosystems. Possible benefits for carrying out EMW methods within coastal ecosystems are the mechanical energy of tides for increasing weathering of rock dusts, and access to both atmospheric CO$_2$ and the ocean for potential storage.

Concerns with EMW that will need to be addressed are the lifespan of each application of rock dust and the release of potential contaminants from the minerals that are used. Minerals that contain olivine weather fast and increase bioavailability of magnesium and potassium in soils, but also increase concentrations of nickel and chromium (Berge et al 2012, Beerling et al 2018). The effect of high concentrations of nickel and chromium on blue carbon ecosystems has not been well studied, but it has been an issue in agricultural EMW and has been seen to bioaccumulate in marine amphipods following olivine exposure (Flipkens et al. 2023). Further research needs to be done into whether these contaminants will affect the environment, and if so, whether slower-weathering minerals are also effective in EMW.

**Research Approach**

This project will determine how carbon fluxes change with the application of ground silicate rock to the sediments of blue carbon ecosystems, which will help determine whether these methods are a practical form of CDR. For this purpose, plots of soil in mangrove and marsh ecosystems will be selected. Control plots will have no rock dust added, while experimental plots will have rock dust added. The rock dust will be commercially available basalt and olivine, at a size < 50 µm as per Haque et al. 2019. Over the course of the LOREX program, these plots will be monitored for changes in carbon flux to the atmosphere and water. Gas flux will be determined via in situ sediment-air and sediment-water incubations of the plots using incubation chambers available at the Centre for Coastal Biogeochemistry (CCB). This will be done with chambers that seal out the atmosphere and input air into an instrument that monitors for CO$_2$ and methane concentrations (LICOR 7810 trace gas analyzer). To determine changes in porewater chemistry, porewater wells will be placed in the sediment using piezometers to extract water samples. Porewater samples will be tested for total alkalinity, dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and trace metals (via ICP-MS), all at the CCB. These analyses will be used to determine changes in the porewater chemistry over time and used to determine the biogeochemical reactions occurring
Water samples will also be analyzed for contaminants that may be released by the weathering of the minerals, as this is a concern of the application of rock dusts for EMW.

Data collected will be used to determine changes in carbon fluxes for blue carbon ecosystems following the application of EMW methods, and how these effects change over time. Changing concentrations of CO$_2$ and methane will be converted to fluxes to determine how atmospheric exchanges of carbon change over the course of the experiment. Changing aqueous concentrations of total alkalinity and dissolved inorganic carbon will be used to determine biogeochemical reactions that are occurring in plots. Carbon budgets will be calculated from this data to gain a picture of the overall effects and practicality of using EMW methods as CDR in these ecosystems.

**Project Feasibility**

Project feasibility is based on the availability of rock dust for experimental plots, available equipment for environmental analysis, accessibility of ecosystems to be used for experiments, and regulations on field experimentation. Rock olivine dust is available in bulk amounts and has been previously used at the CCB for other laboratory-based experiments (Moras et al. 2022). The CCB has access to the state-of-the-art instrumentation for biogeochemical analysis, which I will receive training on during this fellowship. Access to marsh and mangrove forests is ideal and there are numerous other research projects that are already working within these ecosystems out of the CCB. Lastly, it is questionable whether local regulations will make it difficult to apply rock dust in pristine estuarine environments, but the minerals will be used in small amounts and are not expected to have a large detrimental impact on the surrounding environment. If there are issues with permitting, experiments can be done in the laboratory on sediments retrieved from these ecosystems, which the CCB already has permits for.

**Why the project is needed**

This project is needed because the development of carbon capture technology is essential for the slowing of anthropogenic climate change. While reduction of the use of fossil fuels is essential for reducing the release of greenhouse gases, the concentration of CO$_2$ in the atmosphere is already too high to allow for reversal of the process by natural means. Methods of carbon capture have been developed, but the effectiveness of these strategies needs further investigation. Increasing the amount of carbon capture strategies allows for greater diversity of options for reduction of atmospheric carbon, and allows for enhancement of natural processes that are already storing carbon.

**Dissemination of results**

Results from this investigation will be used as a chapter in my thesis and published within international journals. I will also disseminate these results at an international conference such as the Ocean Sciences Meeting. Finally, I plan to give a special seminar to the School of Earth, Environment, and Sustainability detailing my work when I return to Georgia Southern University in the Fall of 2024.
Project Justification

This project will lead to the development of new Carbon Dioxide removal (CDR) methods. CDR technologies are essential in plans to reduce concentrations of greenhouse gases in the atmosphere. While current CDR methods exist, utilization of multiple methods is important in maximizing future carbon capture. Blue carbon ecosystems are already capable of capturing carbon through living biomass and export of dissolved inorganic carbon to the ocean, and this project would investigate enhancing this natural process with the application of EMW methods, which have already been found to be an effective CDR technique in agriculture (Beerling et al. 2018). The application of ground silicate rock has been found to have positive effects on the health of crop plants (Berge et al. 2012), so this method may have the added effect of improving the productivity of blue carbon ecosystems.

The Centre for Coastal Biogeochemistry has expertise in alkalinity measurements and environmental measurements in blue carbon ecosystems. This makes the facility and faculty at this location ideal for hosting this project, and allowing it to be carried out in the necessary timeline of the exchange program. There is already research at this institution dealing with carbon cycling in mangroves, seagrasses, and coral reefs, which covers methods of environmental sampling that are needed for this project. While experimental application of silicate mineral dust diverges from the current research goals of the facility, it adds diversity to the research that is currently being done and closes knowledge gaps of the application of EMW techniques to Australian blue carbon ecosystems.

Applying EMW methods to Australian blue carbon ecosystems will contribute to my thesis as it adds additional estuarine ecosystems to research the effectiveness of EMW for CDR in coastal ecosystems. As the research is currently based in Georgia, the only blue carbon ecosystem available for research is Spartina salt marshes. While researching EMW effectiveness for this specific ecosystem will allow for application of these methods on the North American Eastern Seaboard and other coastal areas dominated by salt marsh, but investigation of this method in various coastal ecosystems expands the applicability of this knowledge to those ecosystems. While most of my research will still be on Spartina marshes, research on other ecosystems will reveal knowledge gaps and kick off further research into how EMW methods will work in these areas. This research will add to my career goals, as it will add to my breadth of knowledge in carbon capture technology, and allow me to network with other professionals in the field of carbon cycling. Access to instrumentation for tracking carbon fluxes and environmental analysis will also give me experience with the various tools needed for continuing this type of research past my program at GSU. Much of the instrumentation that is available at the CCB is not available at GSU, so this opportunity would give me training and experience in different instruments, data analysis methods and field work that I do not have access to at my home university.
References


19th December 2023

Prof. Bradley Eyre
Centre for Coastal Biogeochemistry,
Faculty of Science and Engineering
Southern Cross University, Lismore, Australia

Prof. Adina Paytan
Limnology and Oceanography Research Exchange (LOREX)

Dear Prof. Adina Paytan and members of the LOREX review panel,

Re: Letter of support – James Westphalen

This letter is to confirm that I enthusiastically support James Westphalen and his proposal on carbon capture utilizing enhanced mineral weathering in Australian mangroves, seagrasses and coral reefs. The Centre for Coastal Biogeochemistry and Faculty of Science and Engineering (Southern Cross University) will host James for the duration of the LOREX exchange, and provide further mentoring to James after the exchange period is complete.

James’s proposed research is strongly aligned with our research areas and expertise, while also providing an opportunity to build new knowledge within the Centre for Coastal Biogeochemistry. We have world-class laboratory facilities and expertise in alkalinity measurements and field measurements in mangroves, seagrasses and coral reefs. Reflecting this, our research group has consistently achieved the highest possible ranking in geochemistry in national research reviews since 2010. As such, we are ideally suited to assist with James’s proposed project. We anticipate that the proposed exchange will positively impact our research group, as well as being of great value to James. We currently have 16 PhD students and 8 postdoctoral fellows and academics within our research group, providing a dynamic environment for exchange of ideas and expertise. James’s project will specifically provide valuable insight to assist with interpretation of the outcomes of Australian Research Council funded research currently underway on carbon cycling in mangroves, seagrasses and coral reefs. Furthermore, James’s project is centered on enhanced mineral weathering, which is something we have not previously done. As such, this opens the way for new areas of research for our team of biogeochemists.

I have exchanged emails with James and are confident that he has the knowledge and drive needed to successfully complete her proposed research. We look forward to working with him both within and beyond the scope of the LOREX program.

Sincerely,

Prof. Bradley Eyre

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CRICOS Provider 01241G
January 3, 2024

Dear LOREX Selection Committee,

It is with great pleasure that I write a recommendation letter for James Westphalen for the LOREX Exchange Program. I first met James in 2020 as a student in my Scientific Communication course at Nova Southeastern University. After that course, James approached me about doing his MS thesis project in my lab and we both agreed it was a good fit. Since then, he graduated from Nova Southeastern with an MS and came to Georgia Southern University with me to complete a PhD in Environmental Science. Over the past 3 years, I have gotten to know James well through various interactions including both course and research related and feel I can adequately comment on his potential as a LOREX exchange student.

James came into my laboratory interested in pursuing a project on coastal biogeochemistry but wasn’t sure about the topic. After many conversations we agreed that pursuing the carbon cycle of beached *Sargassum* was a feasible project in the timeline he had to finish. He immediately took to the project and developed it into his own. James constructed mesocosms from scratch to do a study on the carbon dioxide and methane emissions during the *Sargassum* decay process. Despite many different challenges, James persevered and ended up writing a thesis that I am proud to be his advisor on.

Due to Covid and other circumstances we had to change James’s project dramatically from what was in his original thesis proposal. This required that James adapt his project from a field-based to laboratory-based study. James took this in stride and developed a rigorous experimental approach to his project from the ground up. Despite never having designed mesocosms before, James was able to build 12 different mesocosms with various recirculating seawater systems designed to mimic tides. James was able to build these systems in a short time frame in order to get his project done in time for a graduation deadline of December 2022. During this period, James worked well under pressure and showed true independence.

James has shown great promise as an independent scientific thinker. Of all my graduate students, James has shown the most initiative to learn about new topics and think through scientific problems. This is no doubt why he was able to go from designing an experiment to running it (twice) and analyzing the data within a 3-month period. James is able to see the big picture and put scientific results into relevant frameworks.

James is an excellent writer. He understands the use of structure in writing and is able to build narrative into his scientific writing. I have no doubt that he will excel in producing scientific manuscripts. After working closely with him for the past two years now, I can confidently say that James is both an excellent student and researcher.

James has also shown exemplary leadership skills and ability to work in and lead a team. He has taught other students how to run instruments in my laboratory and has shown strong capabilities...
to collaborate with a diverse group of people, even under strenuous field conditions. James is always organized and has conducted his research with minimal input from me.

I was a PhD student myself at the Southern Cross Centre for Coastal Biogeochemistry under Bradley Eyre and am sure James will excel during this program. He will have access to state-of-the-art biogeochemical instrumentation and technology which will expand his technical abilities and expertise. In the context of modern climate mitigation, James’s project is critical. There is a large initiative underway to conduct enhanced weathering in a range of ecosystems, from the land to the sea. James’s project will shed light on the feasibility and safety of enhanced weathering in coastal blue carbon ecosystem.

Based on my experiences, I think James will make an excellent LOREX Exchange student and fully support his application.

Sincerely,

Tyler Cyronak
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