School of the Environment

Jennifer Kroeger

How I Wrote My Prospectus

Prior to actually drafting my prospectus, I spent significant time outlining each of the chapter/project ideas, ensuring the projects were novel (and doable). I also investigated comparable literature to gather methodology ideas. Once I had a clear outline of my proposed projects (and approval from my advisor that those projects would be sufficient), my next step was writing very rough drafts of each chapter to get an idea of where I needed to gather more literature evidence, or investigate methodologies further, to be able to fully describe and defend the project proposals. Then, with that information gathered, I was able to write a ~full~ rough draft (with citations), send to my advisor for a round of edits, and then make additions and corrections accordingly before sending the final version to my committee.

Because of the timing of this process in my cohort, and differences in expectations between departments and advisors, my prospectus was not a heavily edited, heavily scrutinized piece of prose. Rather, it was written and evaluated based on two main criteria: 1) Are my research objectives novel and impactful? (i.e. do they clearly address stated gaps in the research field?), and 2) Are the stated objectives and methods feasible for me to complete in the time I have remaining in the program?.

Advice for Prospectus Writers

For grad students beginning the process of writing their prospectus, I would advise two things. Firstly, it will be much easier for you to figure out what further research you need to do for your prospectus once you have a rough draft, and thus have an idea of which sections are most challenging to clearly articulate. It's also easier for your advisor to provide recommendations once you have something tangible to work from. Secondly, remember that your prospectus is only a prospectus. Your hypotheses and research questions and methods and potential conclusions are likely to change as you actually do the work, so it's not worth toiling too much in the details when this document is only meant to be a proposal.

Life Cycle Sustainability Assessment of Carbon Dioxide Removal Via Enhanced Rock Weathering

Dissertation Prospectus: Yale School of the Environment

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Dissertation Prospectus Abstract

Enhanced rock weathering (ERW) is a proposed climate solution that aims to accelerate earth's natural rock weathering process onto human timescales to mitigate greenhouse gas-driven global climate change. Ongoing research addresses biogeochemical ramifications of ERW application on land and ocean areas. Research also explores the full life cycle impacts to enable effective implementation for optimal carbon sequestration. As of early 2024, only a handful of standard life cycle assessments (LCA) of ERW have been published. This dissertation prospectus describes four LCA-based projects aimed at providing more robust, regional assessment of the net life cycle environmental impacts of ERW to support deployment. Chapter 1 introduces the primary concepts of this planned dissertation and relevant literature, namely carbon dioxide removal (CDR), ERW, and LCA. This chapter also provides a review of ERW characteristics that are relevant for LCA assessment. Chapter 2 showcases a publication of a waste-based ERW LCA study, and proposes a secondary study exploring the logistics and ramifications of co-benefit inclusion in an ERW LCA framework. Chapter 3 proposes a study to quantify [redacted] And finally, Chapter 4 proposes an exploration into utilizing [redacted] In combination, these four studies will advance fundamental knowledge and provide practical insights for the sustainability evaluation of ERW for future implementation.

Chapter 1: Introduction

1.1 Carbon Dioxide Removal Via Enhanced Rock Weathering

The sixth assessment report from the United Nations' Intergovernmental Panel on Climate Change (IPCC) reaffirms global goals to limit warming to under 2˚C to avoid severe environmental impacts[1]. IPCC models show that carbon dioxide removal (CDR) from the atmosphere, in addition to greenhouse gas (GHG) emission reduction, is necessary to meet internationally-recognized climate change mitigation goals[2]. CDR methods, which are also commonly referred to as net emissions technologies (NET) or in some cases natural climate solutions (NCS), move CO_2 from the atmosphere into earth system sinks. Land-based CDR strategies include biologic sequestration from photosynthetic pathways (afforestation and reforestation, biochar, bioenergy, soil carbon sequestration), geochemical pathways (enhanced rock weathering, wetland restoration), and chemically engineered pathways (direct air capture)[3]. Enhanced rock weathering (ERW, also called 'enhanced weathering' or 'enhanced silicate weathering') refers to the process by which the rate of chemical rock weathering is increased to uptake CO_2 on human timescales. The ERW CDR pathway has recently drawn increased interdisciplinary interest as a deployable climate solution.

Since the late 1800s, scientists have understood that silicate weathering and carbonate precipitation regulate CO_2 levels that influence Earth's climate[4]. This cycle, referred to as the Urey reaction and equilibrium, buffers climate on a 100 million year timescale inorganically[4,5]. The Urey reaction describes the mechanism behind climate cooling that occurred during previous tectonic uplifts of weatherable material in Earth's history[5]. With exposure to atmospheric CO_2 and H_2O, silicate rock dissolves into magnesium, calcium, and/or iron cations and bicarbonate products. Bicarbonate is eventually mineralized and deposited in oceans as carbonate rock ($CaCO_3$)[6]. This chemical reaction was first proposed by Seifritz in 1990 as a natural process that could be leveraged to purposely sequester carbon on short timescales[6]. While Seifritz postulated this reaction taking place in a contained space where CO_2 would be pumped over silicate materials, the methodology has evolved to assume that ERW would be accomplished by spreading rock material over land and water areas.

In addition to the removal of atmospheric CO_2 via bicarbonate transport and carbonate precipitation, another crucial advantage of ERW implementation is its geochemical impact to soil and oceanic alkalinity. As rock material is weathered, the release of magnesium and calcium cations introduces alkalinity to soils, as well as aqueous bodies subject to product runoff[7]. Alkaline soils (pH>7.5) can restrict plant growth, but the majority of cropland area is subject to growing acidity due to continued fertilizer nitrification, organic matter buildup, and general overuse[8,9]. In fact, farmers often purchase fertilizers, including limestone to specifically counteract acidity, to avoid crop degradation that can result from overly acidic soil environments. ERW's alkaline inputs can therefore act as a critical replacement of nutrients when applied on land, particularly on croplands that stand to gain the most co-benefit from changing soil alkalinity[10,11]. Silicate rock used for ERW also introduces potassium (K) and phosphorus (P) to soils when dissolved, which are other nutrients critical to plant growth[12,13]. In aqueous systems, water acidity continues to climb as increasing amounts of CO_2 from the atmosphere are dissolved into solution[14]. Acidification, particularly in the oceans, has been shown to be detrimental to carbonate-based species, like coral, that rely on mineral assemblages for their skeletal structure[15]. Runoff from land-based ERW and ERW applied to coastal and aqueous bodies can introduce alkalinity to help counteract this increasing acidification[7,16]. Thus, the alkaline products of ERW have significant environmental effects beyond CDR that make ERW a promising climate change mitigation tool.

Recent ERW literature has focused on a large breadth of ERW characteristics. Firstly, ERW literature from the last decade broadly has aimed to better characterize the expected net CDR from the strategy in different biogeochemical circumstances. This literature has utilized geologic and soil modeling, namely reactive transport models and weathering rate models, to determine estimates of tonnes per year that could be removed with ERW applied to land[17,18]. Literature has concluded that ERW could sequester between 0.5 and 5 Gt of CO_2 per year if implemented globally[17,19,20]. More recent literature evaluating the CDR potential of ERW has also focused on the timing of dissolution to understand when permanent carbon sequestration or associated co-benefits would occur following application[21,22]. Focus on the CDR potential of ERW has also prompted a recent literature surge regarding MRV (monitoring, reporting, verification) methods for ERW CDR. This area of literature aims to understand how scientists and practitioners can quantitatively prove the amount of CDR realized through ERW application[23,24]. MRV of CDR is critical as projects, including ERW, are introduced as purchase options in the voluntary carbon market (VCM)[25]. Verifying CDR from ERW faces challenges due to the uncontrolled field conditions in land application, as well as optimizing what soil or water measurements best show and connect geochemical changes to actual atmospheric carbon removed[26].

In addition to ERW CDR accounting, recent literature has aimed to investigate more unconventional logistics and opportunities for ERW implementation. A number of studies explore the potential of utilizing non-mined source materials for ERW projects. For example, Jia et al. 2022 and Zhang et al. 2023 evaluate the potential for enhanced weathering using non-hazardous industrial waste[27,28]. Renforth et al. 2011 evaluate industrial waste use for enhanced weathering, along with construction and demolition wastes[29]. This literature provides a foundation for incorporating circularity in ERW project planning. Additionally, an increasing number of studies are expanding on the potential co-benefits of ERW. Direct changes to soil alkalinity, and subsequent alterations in soil nitrogen cycling, have been shown to decrease N_2O emissions from application lands[30–32]. Increases in soil health from ERW alkalization have been found to increase crop yield in both lab experiments and a field experiment in the Midwest U.S[31,33,34]. Literature has postulated that realization of these impacts, as well as direct P and K additions to soil, from ERW would also impact fertilizer purchases and application, creating another indirect co-benefit from ERW deployment[35]. Ocean alkalinity from dissolved ERW products can also mitigate negative impacts from ocean acidification[36].

Despite CDR potential and additional environmental benefits from application, ERW has embodied emissions from sourcing, grinding, transport, and application processes. Energy required for these stages of the ERW life cycle have been intermittently reported in literature. Some studies, such as Renforth 2012, include proportion-based estimates for the percentage of CDR negated by upstream GHG emissions[18]. Other publications, such as Moosdorf et al. 2014 and Strefler et al. 2018, provide estimates of energy penalties for ERW grinding and transport processes[20,37]. As of early 2024, five life cycle assessment (LCA) studies for ERW have been published. Lefebvre et al. 2019 and Eufrasio et al. 2022 provide LCA for land-based basalt ERW across a range of environmental impact categories using the CML and ReCiPe assessment methods, respectively[38,39]. Foteinis et al. 2023 provide an LCA of olivine-driven ERW in coastal environments[40]. Cooper et al. 2022 conduct an LCA of ERW in North America in a comparison of

CDR methodologies[41]. And Oppon et al. 2023 compare LCA results of basalt rock dust fertilizer to those of standard fertilizers for crops[42].

1.2 Life Cycle Assessment for CDR Evaluation

LCA, one of the central paradigms in the field of industrial ecology, is a methodology used to analyze the environmental impacts over the entire life cycle of a product, process, or service. A standard LCA is comprised of four steps specified by ISO standard 14044: definition of goals and scope of an assessment (1), an inventory of inputs and outputs of life cycle stages (2), a detailed assessment of environmental impacts resulting from this inventory (3), and interpretation of results to identify hotspots of high impact and strategies for reducing environmental burdens (4)[43]. Standard LCAs also rely on the definition of system boundaries within which the assessment is conducted and relevant, and functional units of results that relate data to the subject's function.

LCA has been utilized to evaluate many types of CDR pathways. Terlouw, et al. conducted a review in 2021 of LCAs for a set of CDR technologies, including forestation, bioenergy with carbon capture and storage, biochar, direct air capture, and ERW[44]. This paper found that while some technologies, like biochar, had dozens of associated LCAs, other technologies like ERW or direct air capture only had a few. [redacted] Additionally, as the VCM expands as a net zero mechanism for the business sector, guidance protocols established for CDR project evaluation require LCA results in order for projects to be approved. Thus, LCA of CDR fulfills a clear need [redacted]

1.3 Key ERW Characteristics in LCA and Environmental Impact

Robust LCA literature for ERW is critical for identifying impactful hot spots in the strategy's life cycle and maximizing environmental benefit. The following paragraphs review LCA-relevant considerations of each stage of the ERW life cycle (material sourcing, comminution, transport, and application).

Raw Material Extraction

The first life cycle stage of ERW is the extraction of raw rock material in mining operations. Basalt and olivine are commercially mined at a global scale as construction materials, meaning that mining operations and infrastructure are in place for future ERW deployment[18,46]. Olivine is highly weatherable due to its mineral arrangement, but its high heavy metal content (nickel and chromium) creates potential contamination risks in application if the metals are washed into watersheds and contaminate flora and fauna[47,48]. While basalt does not have the same heavy metal content, it also has a lower CDR yield potential than olivine, meaning that it has a lower

CO_2 removal potential[20,49]. This difference can impact the results of an LCA significantly in balancing energy inputs with a functional unit of tonnes of CO_2 sequestered.

Depth and thickness of the strata targeted for mining can also impact energy requirements. Deeper mining requires greater fuel inputs[18]. Mining locations in relation to application site climate also impact LCA calculations. For example, olivine formations are found in many tropical regions where application in warm and moist conditions could allow for efficient weathering[50]. Energy inputs and environmental impact in the mining life stage can be mitigated if waste products are utilized for ERW. Basalt powder is often stockpiled as a waste product in mining operations, and could be allocated for ERW application with little-to-no energy input[51].

Comminution

Grain size is one of the primary controls on ERW's net CDR due to its influence on the weathering rate and the energy inputs required to crush and grind the rock material. Comminution, along with transportation, accounts for up to 94% of the energy required in an ERW life cycle[18]. Mining and grinding together are thought to reduce ERW net CO_2 sequestration by 5-10%[50]. Energy inputs for crushing and grinding include electricity to support site operations at a fixed plant, and screening and crushing equipment that require diesel fuel. A typical industrial pathway of crushing and grinding proceeds from primary stage crushing to secondary and tertiary crushing that utilizes screens to cycle out ultra-fine particles[51]. Literature does not address whether grinding infrastructure exists onsite at mining, but Lefebvre et al.'s ERW LCA find that comminution activities offsite increase transportation logistics and distance and thus increase fuel use[38].

Particle size is an important consideration both for fuel use and sequestration potential. Smaller grains with more irregularity, and thus more surface area, result in greater CO_2 sequestration, but also greater energy inputs along the grinding pathway[20]. Literature also suggests that particle size is dependent on the mining technique utilized in the first step of the life cycle. If fine dust is collected at mining sites, crushing activities may be limited[13]. Thus, balancing energy inputs and grain size-driven weathering rates for an optimal comminution stage is critical in defining system characteristics in future LCAs.

Transportation

In the existing LCA outlining a Brazilian operation for ERW, transportation represented the greatest energy input into the process[38]. Common transportation modes include vehicle transportation of different sizes, rail freight, and waterway distribution via inland waterways and barge shipping. Identifying the mode that best represents realistic operations is critical for a robust LCA and optimizing ERW pathways from source to application[52]. For example, truck transportation may reduce the net CO_2 removal of enhanced weathering by up to 11%, but waterway distribution has lower GHG emissions by comparison[18,50]. Transportation energy inputs could be lowered through decentralized operations with mining closer to application and road network improvements in regions of application.

Application

The use stage of ERW (application) entails infrastructure considerations. Application of rock materials onto agricultural lands would utilize existing fertilizer application infrastructure, fuel for which would be accounted for in an LCA[38]. Cyclic application versus singular application also alters expected energy inputs in an LCA. Multiple applications increase emissions, but may increase sequestration potential due to increased cumulative rock material application. As outlined above, application of ERW to agricultural land can also beget co-benefits including decreased N_2O emissions, crop yield increases, and subsequent fertilizer avoidance. Field trials are needed to further parameterize these soil interactions[17,53]. Energy inputs from application, as well as environmental impacts from nutrient interactions, are relevant LCA inputs.

Runoff

The last stage in LCA methodology is characterized by the waste, disposal, and/or recycling stages in a product or process lifetime. For ERW application on agricultural lands, this stage is the runoff of materials into watersheds. As mentioned earlier in this prospectus review, olivine application poses risks of heavy metal runoff. Rock material being washed away prior to dissolution can increase water turbidity, which impacts flora and fauna survival[51]. [redacted]

1.4 Addressing ERW LCA Literature Gaps

The four studies proposed in this prospectus address multiple literature gaps that currently exist in ERW LCA.

Previous ERW LCA literature has explored net life cycle environmental impacts of ERW on regional and global scales, but [redacted]. Chapter 2 Part I addresses both of these gaps through an [redacted]

While experimental ERW literature has reported co-benefits from ERW application in both lab and field settings, [redacted] The ERW LCA proposed in Chapter 2 Part II addresses this gap by including [redacted] Additionally, this chapter uniquely compares [redacted]

A handful of ERW publications have discussed the utilization of ERW application on bioenergy crops[31,54], [redacted] This research topic also addresses an identified need for [redacted] There are no previous publications that have quantified [redacted] Chapter 3 addresses this gap by determining [redacted]

Chapter 2 and 3 utilize traditional LCA methodology to evaluate ERW. However, while traditional LCA is the standard environmental impact assessment tool utilized in academic literature and environmental certification structures, [redacted] However, while this framework has been paired with LCA to assess the sustainability of varied products and regions[60–62], it has not yet been utilized to assess the [redacted]amifications of CDR. Chapter 4 leverages the [redacted] addresses this research gap by evaluating [redacted]

Together, these four studies work cohesively to address gaps that currently exist in evaluating ERW with the inclusion of [redacted]. This research will help support optimal ERW deployment in a growing carbon market.

Chapter 2: Life Cycle Assessment of Enhanced Rock Weathering - A United States Case Study

2.1 Background

[redacted] Existing literature [redacted] Previous studies have also discussed [redacted]. Broadly, the literature suggests that global ERW application could sequester 0.5–5 Gt of CO_2/yr[19,50,71]. [redacted]

This dissertation chapter presents a multi-part LCA of ERW in the United States addressing these particular gaps in ERW LCA literature. Part I, titled *Techno-economic and Life-cycle Assessment of Enhanced Rock Weathering: A Case Study from the Midwestern United States*, was published in Fall 2023 in *Environmental Science & Technology* and co-authored by Dr. Bingquan Zhang, Dr. Yuan Yao, and Dr. Noah Planavsky[75]. Text in this introduction, as well as the description below, has been reproduced from this co-authored publication. Part II presents an in-progress research project aimed at understanding the consequences of incorporation of co-benefits into an ERW LCA framework. Text in Part II is original to this prospectus.

2.2. Part I: Techno-economic and Life-cycle Assessment of Enhanced Rock Weathering: A Case Study from the Midwestern United States

[Writing portions excluded for copyright purposes. See https://pubs.acs.org/doi/10.1021/acs.est.3c01658 for published article.]

2.2.1 Introductory Background

[redacted]

[redacted]

2.2.2 Research Objectives

This study addresses the following research questions and tests the following hypotheses.

Research Question 1a: *What are the embodied GHG emissions (eGHG) associated with three main life cycle stages of waste ERW deployment?*

Research Question 1b: Considering eGHG quantified by question 1a*, what is the net CDR and carbon footprint of waste ERW deployment?*

Hypothesis Test 1(a & b): We hypothesize that eGHG emissions from application of waste material for ERW in the Midwest U.S. will vary across a range of CDR application assumptions. We also hypothesize that net CDR and ERW carbon footprint will vary across a range of CDR yield values. We conduct an LCA for transport, comminution, and application of waste ERW to quantify eGHGs, net CDR, and carbon footprint, and test these hypotheses.

Research Question 2: *Which life cycle stages of ERW deployment account for the greatest amount of eGHGs?*

Hypothesis Test 2: We hypothesize that each life cycle stage of ERW will have a different contribution to net impacts quantified in question 1, with application likely accounting for the smallest impact. We test this hypothesis by comparing eGHG inventory for each life cycle stage.

Research Question 3: *What are the sensitivities of the analysis results from questions 1 and 2?*

Hypothesis 3: We hypothesize that ranges of inputs from literature on ERW characteristics, such as mineral type and particle size, and life cycle stage characteristics, including transport mode and distance, will result in a range of values for eGHGs, and subsequently, net CDR and carbon footprint. To test this hypothesis, we utilize ranges of input values from literature to quantify uncertainty of results in a sensitivity analysis included in the publication.

2.2.3 Methodology

LCA Modeling Framework

[1] TEA details are not included in this prospectus, as these elements of the publication were led by co-author Dr. Bingquan Zhang.

[redacted]

[redacted] (2.1)

[redacted] (2.2)

[redacted] (2.3)

[redacted]

[Figure excluded for copyright purposes]

Figure 2.1. [redacted]

Case Study of ERW in the Midwestern U.S.

[redacted]

[2] Appendix A contains the Supplementary Information (SI) for the Chapter 1 Part I publication.

[redacted]

LCA Model

[redacted]

$$[redacted] \quad (2.4)$$

[redacted]

[redacted]

2.2.4 Results and Discussion

Carbon Removal Performance of ERW

[redacted]

[redacted]

[Figure excluded for copyright purposes]

Figure 2.2 [redacted]

Sensitivity Analysis

[redacted]

[Figure excluded for copyright purposes]

Figure 2.3. [redacted]

[redacted]

Implications and Limitations

[redacted]

[redacted]

2.3 Part II: ***Integration of Co-Benefits into Life Cycle Assessment of Enhanced Rock Weathering: A U.S. Case Study***

<u>2.3.1 Introductory Background</u>

As reviewed in Chapter 1 of this prospectus, interest in ERW deployment has been driven partially by potential co-benefits following application. Directly, ERW can help to reverse soil acidity through bicarbonate addition to soil systems and improve crop health through K and P mineral addition[7,13,35]. Subsequent indirect co-benefits from this pH change include decreased N_2O emissions from soil systems, due to changes in nitrogen cycling, increased crop yields from improved soil health, and avoided liming and fertilization[30,32,35,63]. Offsite, research also shows that runoff of dissolved materials into aqueous systems can contribute to reversing ocean acidification, as well as potentially introduce mineral benefits to aqueous species[36].

More recently, an increased number of studies have sought to begin quantifying these co-benefits in both field and modelling experiments. For example, Blanc-Betes, et al. 2020[31] and Kantzas et al. 2022[64] model ERW deployment and model estimates for N_2O reductions and fertilizer avoided from deployment. Chiaravalloti, et al. 2023[32] and Kantola, et al. 2023[33] report N_2O and crop yield changes, respectively, from greenhouse and field ERW experiments

[redacted]

This study will address this research gap by constructing an LCA framework of ERW in the U.S. incorporating [redacted]

Additionally, as of early 2024, four articles have provided LCA results for land-based ERW across a full range of impact categories[38,39,41,42]. However, only one of these previous publications explored the impacts of national supply chain constraints (Lefebvre et al. 2019), and none [redacted]

2.3.2 Research Objectives

This study will address the following research questions and test the following hypotheses.

Research Question 1: [redacted]

Hypothesis Test 1: [redacted]

Research Question 2: [redacted]

Hypothesis Test 2: [redacted]

Research Question 3: [redacted]

Hypothesis Test 3: [redacted]

Research Question 4: [redacted]

Hypothesis Test 4: [redacted]

2.3.3 Data and Methods

[redacted]

[Figure excluded for confidentiality]

Figure 2.4. *System boundary for LCA Part II*

Research Questions 1 & 2

The geographical bounds of this study [redacted] Transport distances will be estimated through [redacted]

LCI data will be sourced primarily [redacted] This is a preliminary data collection. [redacted]

[redacted]	Literature	Direct or Indirect	Quantification

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted] µ [redacted] µmol [redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

	[redacted] [redacted]		[redacted] [redacted]
[redacted]	[redacted] [redacted] [redacted] [redacted]	[redacted]	[redacted] [redacted] [redacted] [redacted]
[redacted]	[redacted] [redacted] [redacted] [redacted] [redacted]	[redacted]	[redacted] [redacted] [redacted] [redacted] [redacted]

				[redacted]

Table 2.1 [redacted] *from literature for use in ERW LCA Part II*

Impacts in this LCA study will be assessed utilizing TRACI and ReCiPe assessment methods[103,104]. TRACI will be used because it is a U.S.-centric tool developed by the U.S. Environmental Protection Agency[104], matching the geographic boundaries of this study. The ReCiPe model, while euro-centric, will also be assessed to allow comparison to existing ERW studies that utilize the ReCiPe assessment method[41,103]. I will conduct this LCA using OpenLCA software.

Research Question 3

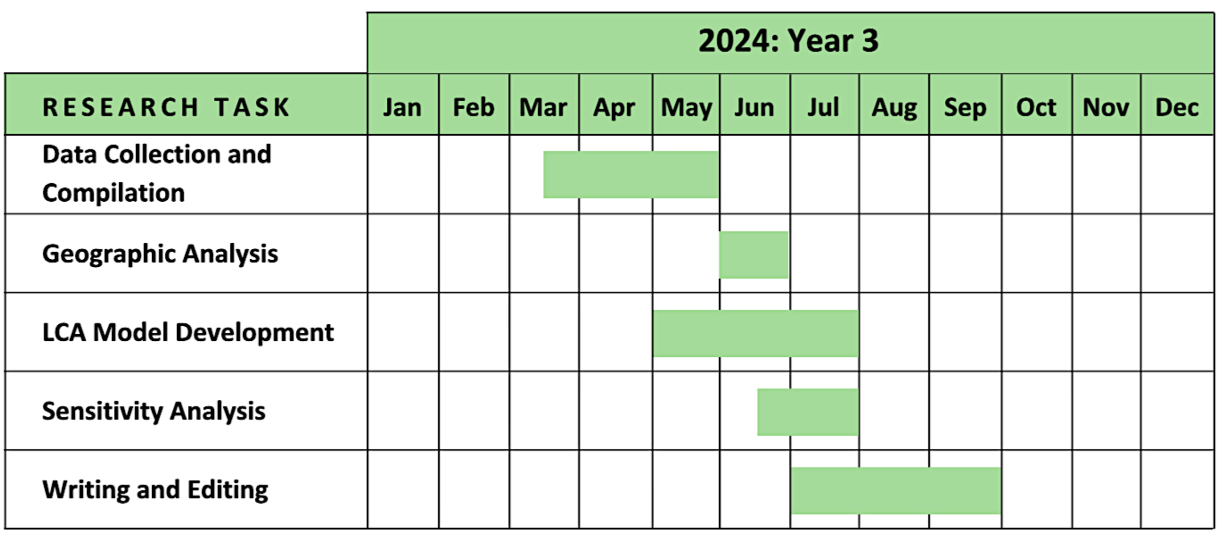
A sensitivity analysis will be conducted to determine the range of LCIA results possible from appropriate ranges of input parameters. Ranges of [redacted] and other project characteristics as defined by the study published as Part I will be used inputs for this sensitivity analysis.

2.3.4 Expected Results and Outcomes

Research Question 4

The framework of this study will provide [redacted] The LCA results will provide useful insights [redacted]

2.3.5 Chapter 2 Part II Timeline



Chapter 3: [redacted]

3.1 Introductory Background

[redacted]

[redacted]

Previous literature has discussed [redacted] However, there remains a gap in the literature for quantifying [redacted] Understanding the decarbonization impact of [redacted] will provide new insights for [redacted]

This project will utilize a life cycle assessment (LCA) framework to [redacted] This study will analyze the impact of [redacted] The results of this quantitative investigation will [redacted]

3.2 Research Objectives

To characterize the environmental impacts of [redacted], this project will answer the following questions and test the following hypotheses.

Research Question 1a: [redacted]

Research Question 1b: [redacted]

Hypothesis Test 1: [redacted]

Research Question 2: [redacted]

Hypothesis Test 2a: [redacted]

<u>3.3 Data and Methods</u>

This project will utilize LCA to assess [redacted]

Research Question 1a

To evaluate [redacted] I will construct [redacted]

I define two existing scenarios, and two novel scenarios, [redacted]

[redacted]

[Figure excluded for confidentiality]
Figure 3.1 *System boundary of LCA Scenarios*

[redacted] Figure 3.2 below provides a visual of the [redacted]

[Figure excluded for confidentiality]
Figure 3.2 [redacted] *pathways proposed for scenario comparison*

The ERW LCI for existing scenario 1 and the ERW component of novel scenarios 1 and 2 will be constructed utilizing data sources detailed in Chapter 2. Specifically, I will use [redacted] I identify [redacted] literature that contains LCI data for [redacted] matching the scope of my proposed study. A preliminary set of this literature is shown in

Table B1 in Appendix B. Additionally, I will validate literature averages for [redacted]

Additional LCI data for [redacted]

(Eq. 3.1) [redacted]

Novel scenario 2 will expand upon the data inventory in novel scenario 1 with the addition of [redacted]

(Eq. 3.2) [redacted]

LCIA results for the scenarios will be evaluated with both TRACI and ReCiPe. TRACI will be used to quantify results in a U.S.-based methodology[104]. ReCiPe will be used to quantify results that are more widely comparable to international LCA studies[103]. [redacted]

[redacted] The LCA results of these scenarios will answer research question 1a [redacted]

Research Question 1b

In order to answer research question 1b [redacted]

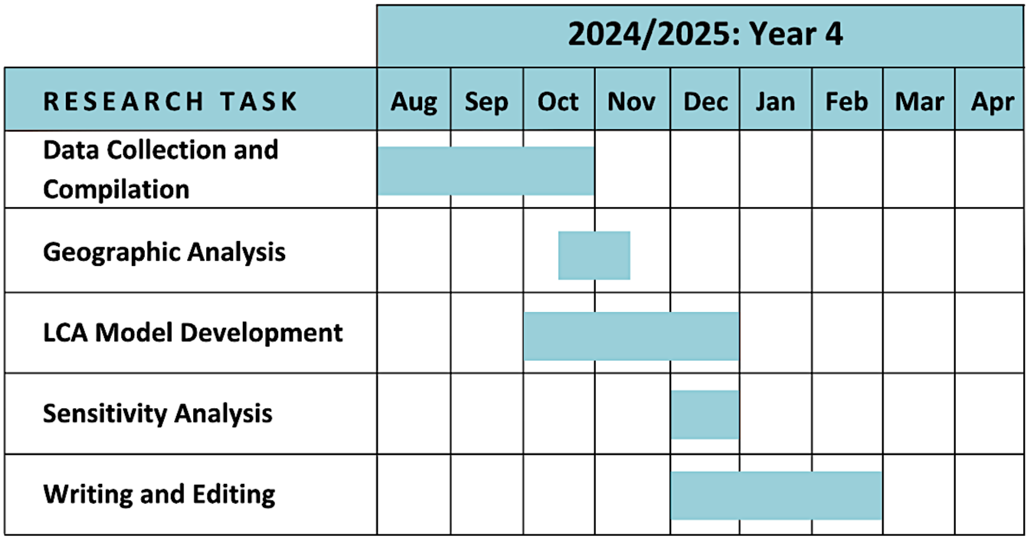
Research Question 2

I will answer research question 2 [redacted] I hypothesize that inclusions in novel scenario 2 [redacted] will be the largest drivers of results for research question 2. I will publish full details from the sensitivity and uncertainty analysis in the paper's supplementary information to ensure transparency as to the significance or insignificance of results.

3.4 Expected Results and Outcomes

This project's quantification of [redacted] The results will give insight as to what ERW's role [redacted] By providing results for different scenarios, [redacted] results of this study will also provide awareness [redacted]

3.5 Chapter 3 Timeline


2024/2025: Year 4
RESEARCH TASK
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Data Collection and Compilation
Geographic Analysis
LCA Model Development
Sensitivity Analysis
Writing and Editing

Chapter 4: [redacted]

4.1. Introductory Background

[redacted]

[redacted]

[redacted]

While [redacted] has been utilized for regional sustainability assessments (e.g., Taiwan, Sweden), industrial process case studies (e.g., laundry processing, tomato production), and company-level footprint, [redacted] has not yet been utilized to understand environmental impacts of CDR strategies[62,143,144,151,152]. Utilizing [redacted] or this purpose would be a unique perspective, i [redacted] This study aims to contribute to the growing field of [redacted] This study will be the first to connect [redacted] to a CDR strategy. More broadly, assessing the impacts of CDR, in this case ERW, according to [redacted] n the context of this prospectus, this study functions as an advanced model [redacted].

4.2 Research Objectives

[redacted] this project will answer the following questions and test the following hypotheses.

Research Question 1a: [redacted]

Research Question 1b: [redacted]

Research Question 1c: [redacted]

Hypothesis Test 1(a-c): [redacted]

Research Question 2: [redacted]

Hypothesis 2: [redacted]

Research Question 3: [redacted]

Hypothesis 3: [redacted]

Research Question 4: [redacted]

Hypothesis 4: [redacted]

4.3 Data and Methodology

Research Question 1

[redacted]

ERW System Boundary

In this project, net environmental impacts of ERW will be assessed within the same system boundary space defined in both Chapter 2 [redacted]

Defining [redacted]

[redacted]

[Table excluded for confidentiality]

Table 4.1 *Proposed* [redacted]

Upscaling Methodology

[redacted] Equation 4.1 summarizes the proposed model for this upscaling method, [redacted]

(Eq. 4.1) [redacted]

Downscaling Methodology

[redacted]

[redacted] Equation 4.2 models the scaling of [redacted] while equation 4.3 models the scaling of [redacted]

(Eq. 4.2) [redacted]

(Eq. 4.3) [redacted]

Equation 4.4 models [redacted]

(Eq. 4.4) [redacted]

Research Question 2

A contribution analysis of LCA results from the upscaling process will determine which life cycle stages have the greatest impact to results in the [redacted]. Contribution analysis will be conducted utilizing output from OpenLCA.

Research Question 3

Uncertainty and sensitivity analysis will be conducted to determine the range of environmental impact results in this study. Ranges for ERW characteristics utilized in Chapter 2 Part I will be replicated (albeit with updated literature) alongside [redacted] (Chapter 2 Part II) and transport ranges determined for research question 1. Uncertainty analysis in a monte carlo simulation will be utilized [redacted] However, a sensitivity analysis will also be conducted for the initial upscaling of ERW because variables are not independent from one another in regards to ERW characteristics (i.e., particle size may inform CDR yield, etc.).

Research Question 4

Challenges and opportunities for using [redacted] evaluate CDR will be assessed qualitatively throughout the course of the project. Reflections will be presented in publication discussion. “Challenges” will be characterized by [redacted] For example, [redacted] “Opportunities” will be characterized by significant results (i.e [redacted] By including this discussion, I aim to determine how assessment using [redacted] could address desired outcomes expected from [redacted].

<u>4.4. Expected Results and Outcomes</u>

[redacted] As such, this research will provide a new perspective in the [redacted] and contribute to its expanding catalog.

<u>4.5 Chapter 4 Timeline</u>

[Figure excluded for confidentiality]

Prospective PhD Timeline

Calendar Year	2024				2025				2026
PhD Year	Year 3		Year 4				Year 5		
Term	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring
PhD Requirements	Qualifying Exam						Dissertation Defense		
Chapter 2	Data Analysis		Writing						
Chapter 3			Data Analysis		Writing				
Chapter 4					Data Analysis		Writing		
Teaching Requirements			TF #3		TF #4				
Teaching Certificate			Workshops 1-2; Obs 1& 2; Learning Community #1		Workshops 3-5; Obs 3 & 4		Workshops 6-8; Learning Community #2		Portfolio & Exit Interview

Citations

[Excluded in this example, 173 total citations]

Appendix

Appendix A: Chapter 1 Part I Supplementary Information

[Supplementary Information excluded for copyright purposes. See https://pubs.acs.org/doi/10.1021/acs.est.3c01658 for published SI.]

Appendix B

Article Title	Authors	Year	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

Table B1. *Literature* [redacted]