# Final Report
# Coastal Wetland Carbon Sequestration in a Warmer Climate

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**Executive Summary**

Coastal wetlands are global hotspots of carbon storage and locations where carbon and nitrogen cycles have a disproportionately large impact on land, water, and air in comparison to the area they occupy. The extremely high rates of carbon sequestration in these systems are the result of complex feedbacks between vegetation and the physical environment. Complex feedbacks are nascent or absent in ecosystem- and global-scale numerical forecast models. The goal of this proposal was to address the uncertain response of the coastal carbon sink to climate change, a critical knowledge gap in coastal carbon research and a significant barrier to incorporating coastal wetlands into Earth System Models.

The Salt Marsh Accretion Response to Temperature eXperiment (SMARTX) was designed to understand the ecosystem-scale consequences of warming and elevated $CO_2$ ($eCO_2$) in tidal wetlands at the coastal terrestrial-aquatic interface. We successfully designed and built a novel whole-ecosystem warming and $eCO_2$ experiment in a coastal wetland. The gradient design of the warming treatments (+0, +1.7, +3.4, +5.1 $^{o}$C) allowed us to discover unexpected non-linear and non-additive responses arising from plant-microbe interactions. Changes in root-to-shoot allocation by the dominant sedges in this ecosystem were non-linear, with peak belowground allocation occurring at +1.7 °C. Above 1.7 °C, allocation to root versus shoot production declined with increasing warming such that there were no differences in root biomass between ambient and +5.1 °C plots. Elevated $CO_2$ altered this response when crossed with +5.1 °C, increasing root-to-shoot allocation due to increased plant nitrogen demand and, consequently, root production. We suggest these non-linear responses to warming are caused by asynchrony between the thresholds that trigger increased plant nitrogen (N) demand versus increased N mineralization rates. The resulting shifts in biomass allocation between roots and shoots have important consequences for forecasting terrestrial ecosystem responses to climate change and understanding global trends.

We successfully refined an ecosystem-scale model of soil elevation change and carbon sequestration to include the influence of plants on soil organic matter decomposition rates. It forecasts that $eCO_2$ will dramatically increase the stability of tidal wetland carbon pools to the threat of accelerated sea level rise. In addition, we advanced the capability of DOE models to capture terrestrial-aquatic interface biogeochemical processes by adding estuarine anaerobic biogeochemistry to PFLOTRAN and coupling that to the Earth Land Model (ELM).

Changes in $CH_4$ emissions are an important feedback on greenhouse gas emissions in all terrestrial and wetland ecosystems. We found that warming of 5.1 °C doubled $CH_4$ emissions but $eCO_2$ cut then by half. We hypothesize that plant traits dictate how $CH_4$ emissions respond to climate change, and report that experiments do not consider plant and microbe-mediated interactions will miss important non-linear and non-additive responses.

The grant contributed to the professional development of 4 post-doctoral Fellows, 6 undergraduate students, 1 graduate student, 10 technicians, and 30 citizen scientists, and was communicated to colleagues in 16 talks and 5 publications.

## Report

### I. Background

Coastal wetlands are global hotspots of carbon storage. Marshes, mangroves, and seagrass meadows account for about half of the total marine soil carbon budget and bury carbon at rates roughly equivalent to terrestrial forests despite occupying just 2.5% of Earth's land area. Such extremely high rates of carbon sequestration are attributed to high rates of plant production, low rates of decomposition, and sea level rise. As rates of sea level rise accelerate, coastal wetlands have the potential to sequester soil carbon at increasingly rapid rates as long as plants survive flooding and contribute to soil building. Compared to upland soils, the sequestration potential of tidal wetland soils is extremely high because rising sea level increases the potential soil volume over time, and therefore reduces carbon saturation effects typical of upland soils. Coastal wetlands have recently been recognized as important carbon sinks, and therefore the response of carbon cycling to global change in this ecosystem is virtually unexplored. The future sink strength and carbon stock stability of these systems is uncertain because global change drivers such as temperature and elevated $CO_2$ perturb the complex biotic and abiotic feedbacks that drive high rates of soil carbon sequestration. The dynamics of coastal wetland carbon pools are not presently represented in earth system models.

### II. Objectives

Our goals are to quantify how warming affects the stability of large coastal wetland soil carbon pools, the ability of coastal wetlands to maintain contemporary rates of carbon sequestration, and to quantify interactions between temperature, elevated carbon dioxide and inundation frequency on soil carbon dynamics. Here we access our accomplishments for each objective.

*Objective 1: Initiate the first active aboveground and belowground warming experiment in a coastal wetland.*

*Objective 2: Test the overarching hypothesis that warming will increase both plant production and decomposition, but that the net effect will be an increase in soil carbon sequestration rate.*

*Objective 3: modify a well-established marsh carbon model to incorporate new insights gleaned from the warming experiment, including the impact of warming on productivity and decay, and interactions between inundation, warming, and elevated $CO_2$ that vary with plant species across real-life wetland landscapes.*

*Objective 4: migrate this refined marsh carbon model into the new wetland-enabled ACME Land Model (ALM), producing the first attempt to capture tidal wetland dynamics in a fully prognostic land surface model with coupled water, energy, carbon and nutrient cycles.*

### III. Accomplishments

#### A. Objective 1: ***Initiate the first active aboveground and belowground warming experiment in a coastal wetland*.**

The Salt Marsh Accretion Response to Temperature eXperiment (SMARTX) has a hybrid design in which temperature is manipulated as a gradient with four treatment levels for temperature (+0, +1.7, +3.4 and +5.1 °C above instantaneous ambient temperature. An important feature of the design is that warming is applied in reference the ambient temperature such that all of the natural variation in temperature with time and soil depth is maintained. Another important and rather unique aspect of the experiment is it warms the entire ecosystem, from the top of the marsh canopy to a soil depth of 1.5 m. This feat required a complex system of sensors and data logger control programs to accomplish (Figure 1).

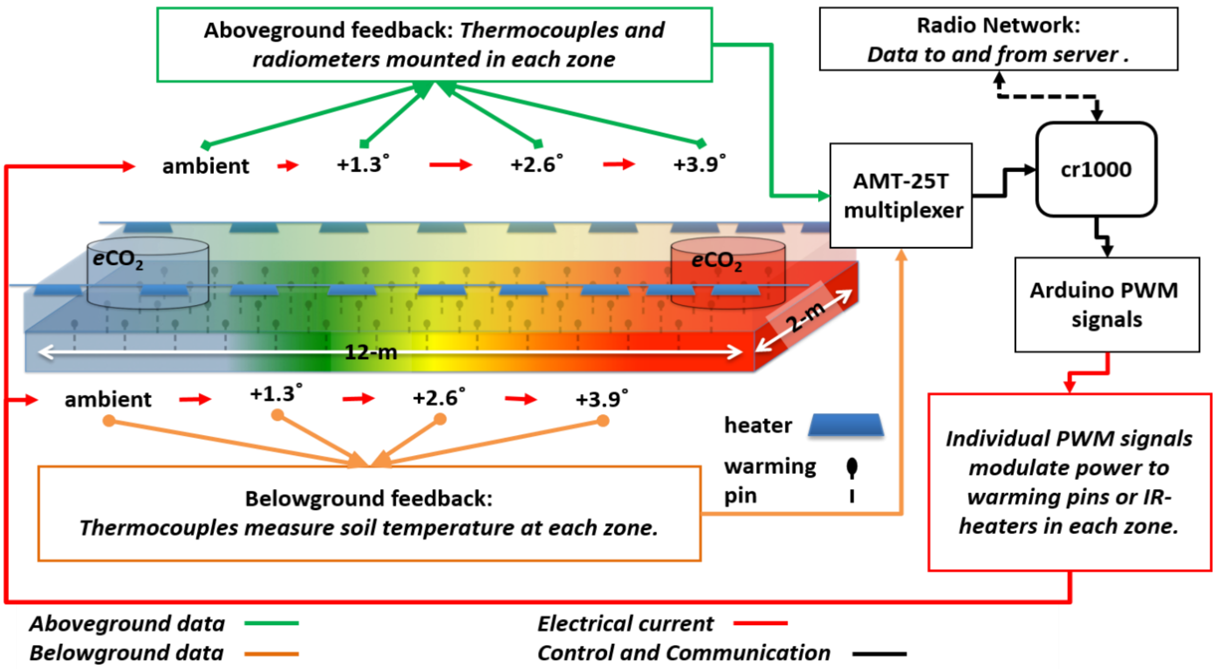


**Figure 1**. Schematic of the general layout and control of each soil warming transect, including infra-red heaters, thermal resistance warming pins, the resulting gradient in temperature, and key features of the feedback control design. Open-top elevated $CO_2$

The experiment is replicated in two plant communities, one that is more frequently flooded and dominated by a $C_3$ sedge species, and one that is less frequently flooded and dominated by a $C_4$ grass species. The warming gradient illustrated Figure 1 is replicated three times in each plant community for a total of six transects. In the $C_3$ plant community only, the two extremes of the temperature treatment (+0, +5.1) are crossed with elevated $CO_2$ set at 750 ppm.

We successfully initiated the first active whole-ecosystem warming experiment in a tidal coastal wetland, and one of only a few in any type of terrestrial ecosystem. The experiment was fully designed and constructed over a nine-month period starting in Sep 2015 and ending in May 2016. The temperature treatments were turned on in early Jun 2016 at which time plants had emerged but the canopy was still developing. Elevated $CO_2$ was initiated the following year in Apr 2017 before plant emergence had begun. Because the 2017 growing season was the first year that we applied both elevated $CO_2$ and warming, we consider 2017 as the first year of experimental data for many analyses. Thus, we focus on the 2017 and 2018 growing seasons in our report.

Temperature control has been excellent with the three heated levels closely tracking the ambient variation aboveground and belowground (Figure 2). Belowground temperature is more stable than aboveground temperature as expected.

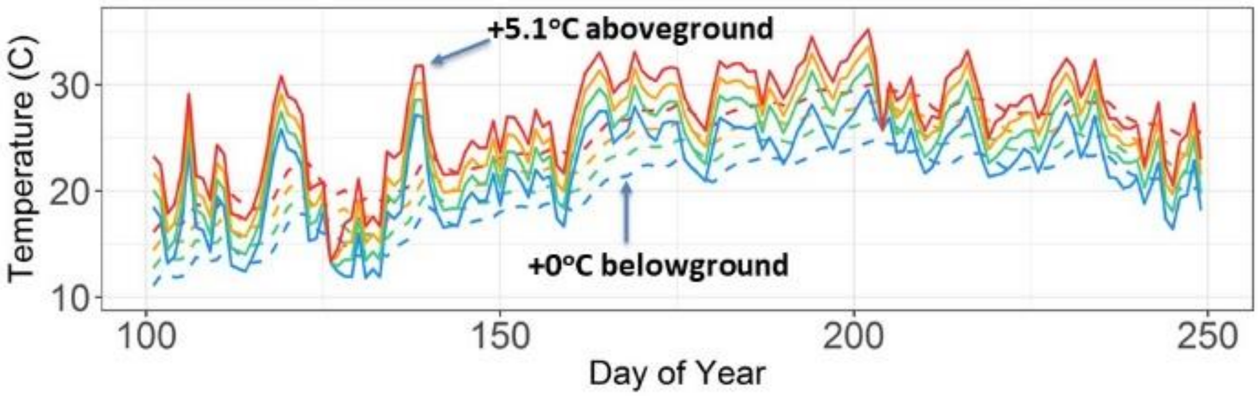


**Figure 2**. Daily aboveground (solid) and 20 cm deep soil (dashed) temperature from Jun to Oct 2018. Blue = ambient, green = +1.7°C, yellow = +3.4°C, and red = +5.1°C.

**B. Objective 2: *Test the overarching hypothesis that warming will increase both plant production and decomposition, but that the net effect will be an increase in soil carbon sequestration rate.***

The overarching hypothesis of the project will require additional years of treatment to fully address because of the relatively slow pace of soil carbon sequestration as expressed by soil elevation gain. However, we can infer the response from significant advances in testing the following sub-hypothesis that concerns primary production:

**H1:** *Warming will increase primary productivity (shoot+root) and decrease root-to-shoot ratio; the net effect will be an increase in belowground production that favors soil carbon sequestration. The interaction of warming and* $eCO_2$ *on belowground production will be additive in the* $C_3$ *community (Figure 3).*

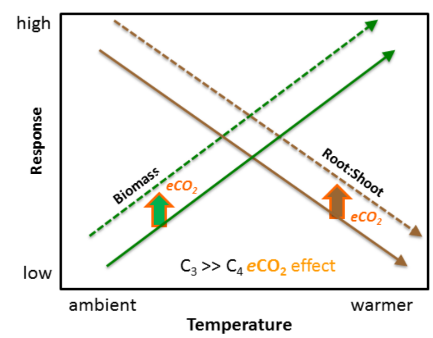


**Figure 3**. Hypothesized effects of warming & $eCO_2$ on biomass and root:shoot ratio. Line slope gives the temperature effect; arrows indicate the interaction of warming and $eCO_2$.

This hypothesis as illustrated was partially supported as illustrated in Figure 3, except responses were not linear as shown but non-linear (Noyce et al. 2019[1]). The $C_3$ and $C_4$ communities responded quite differently to warming, particularly in aboveground biomass ($p=0.01$) (Figure 4).

[1] Noyce, G.L., M.L. Kirwan, R.L. Rich and J.P. Megonigal. 2019. Asynchronous nitrogen supply and demand produce non-linear plant allocation responses to warming and elevated CO2. 116 (43): 21623-21628. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1904990116 (Appendix 1).

Total net primary production (shoot + root NPP) in the $C_3$ community increased at +1.7°C warming, but further warming had no additional effects (Figure 4). By contrast, total NPP in the $C_4$ community declined monotonically with warming (p=0.09). This may have been caused by water stress because these $C_4$ grasses have a shallower root system, and occupy higher, drier areas than the $C_3$ sedge.

Belowground NPP at the $C_3$ site doubled at +1.7°C (p=0.02), but then declined to ambient levels with further warming (Figure 4). However, the decline in root biomass above +1.7°C was compensated by higher shoot NPP. N fertilization produces the same pattern at this site (Langley et al. 2009), suggesting that declining root NPP is a response to a warming-induced rise in N mineralization rates in this N-limited marsh. N limitation is common in tidal marshes, and plants shift allocation to aboveground tissues when N fertilized (Darby and Turner 2008). At our site, and many others, the shift from root to shoot growth has a negative impact on C sequestration, elevation gain, and tidal marsh stability (Langley et al. 2009, Deegan et al. 2012). The result that belowground NPP was insensitive to warming in the $C_4$ community is not inconsistent with higher N mineralization; the dominant $C_4$ species (*Spartina patens*) has a higher $K_m$ for N uptake than the $C_3$ species and may be insensitive to changes in N availability at *in situ* rates of mineralization.

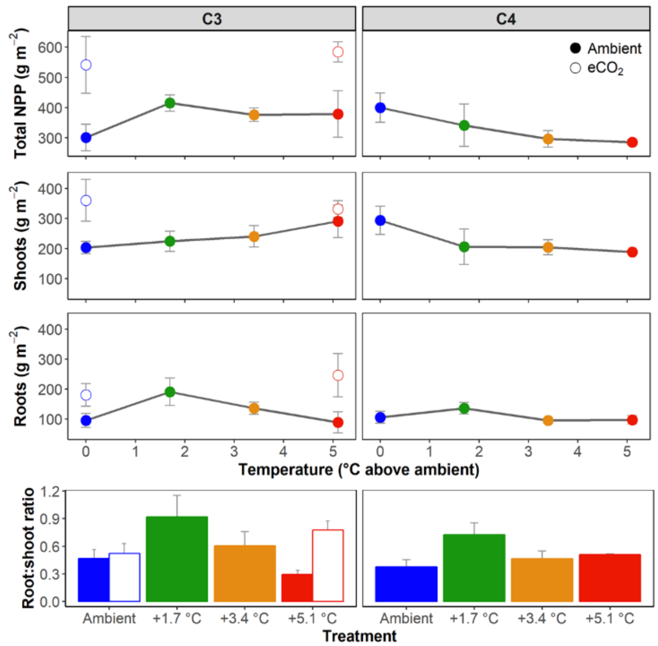


**Figure 4.** Total, shoot and root NPP in SMARTX year 2.

Hypothesis 1 (H1) stated that the effects of $eCO_2$ and warming would be additive and this was the case in the sense that $eCO_2$ increases total net primary production, but decreases the root:shoot ratio by favoring root NPP. At the $C_3$ site eCO2 significantly increased total NPP in the ambient and +5.1°C treatments (p=0.01, Figure 4). The response was primarily due to significant increases in shoot NPP at ambient (p=0.07) and root NPP at +5.1°C (p=0.006) (Figure 2). An increase in root biomass is common in $eCO_2$ studies because higher photosynthetic rates increase N demand for biomass production, which plants satisfy by increasing growth of nutrient-harvesting roots (Langley et al. 2013). High $C_3$ plant investment in belowground NPP at +5.1°C x $eCO_2$ may reflect an increase in N demand, and therefore more allocation of growth to roots. Higher N demand is likely the combined result of (i) $eCO_2$-enhanced photosynthetic rates, (ii) warming-enhanced growth rates, and (iii) the longer growing season with warming. Indeed, warming lengthened the growing season by two months at +5.1°C in both $C_3$ and $C_4$ communities during year 2 of SMARTX. Collectively, warming and $eCO_2$-induced changes in NPP and root-shoot allocation have significant implications for biogeochemical cycling and vertical accretion in coastal wetlands which we summarized in a conceptual model accompanying the first major publication from the grant (Figure 5, Appendix 1).

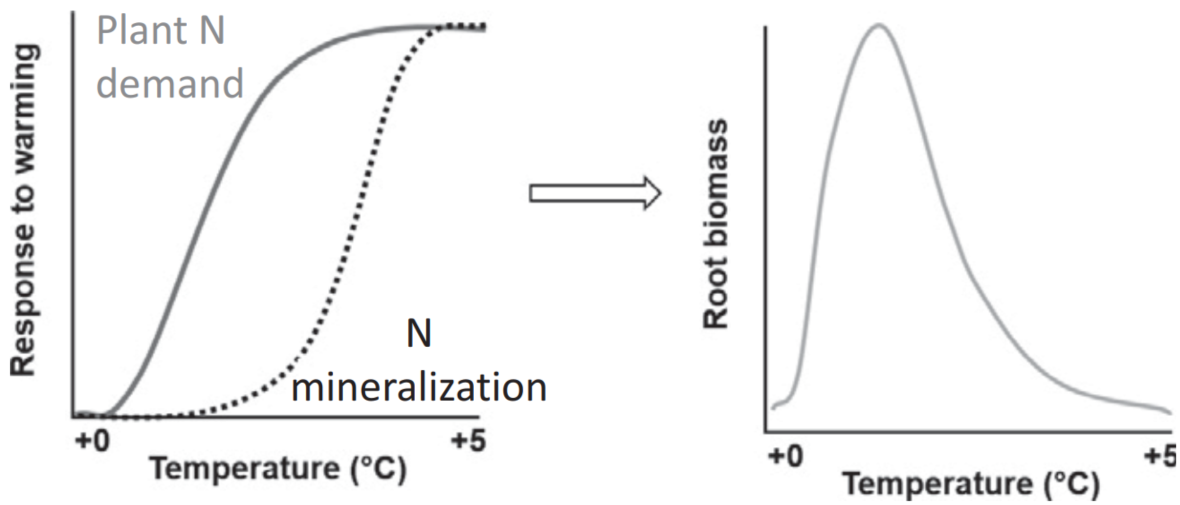


**Figure 5.** Conceptual diagram showing how plants are more sensitive to modest warming than the microbial community, creating a disconnect between plant N demand and N mineralization rates that leads to a large increase in root biomass around 2 °C of warming that declines with additional warming.

**H2:** *Warming will increase decomposition and nitrogen mineralization rates, increasing carbon use efficiency. Increased mineralization rates will be associated with increased aerobic respiration and the labile C supply from more productive plants. The interaction of warming and* $eCO_2$ *on decomposition will be non-additive in both the* $C_3$ *and* $C_4$ *communities (Figure 6).*

Hypothesis 2 (H2) anticipated a linear increase in decomposition expressed as higher rates of N mineralization (Figure 6). We also though $eCO_2$ would stimulate N mineralization in a non-linear pattern (Figure 6). We used porewater $NH_4$ and elevation data to infer that warming hypothesis was supported, but again the response was not linear has hypothesized.

Root:shoot ratio is a sensitive metric of the balance between plant N demand and microbial N supply via mineralization (i.e. decomposition). Warming raised root:shoot ratio and lowered porewater $NH_4$ concentration the lowest warming treatment suggesting that plant demand exceeded supply at +1.7 $^oC$. But above +1.7 $^oC$ warming enhanced N mineralization and the hypothesized linear decline in root:shoot ratio (Figure 7). This non-linear result would not be observed in a two-level design.

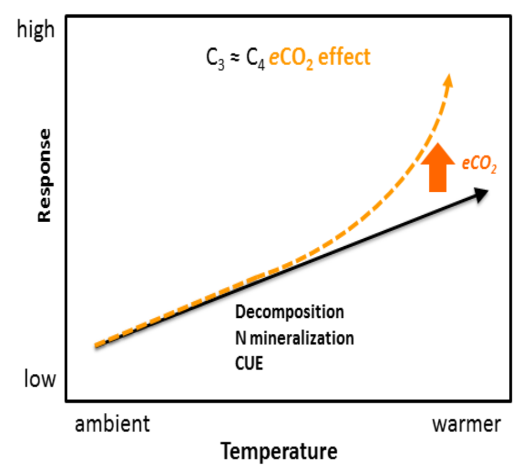


**Figure 6.** Hypothesized effects of warming & $eCO_2$ on SOM decay. Line slope gives the temperature effect. Dashed line indicates that warming increases the $eCO_2$ effects.

The hypothesis about *e*$CO_2$ was not supported. Elevated $CO_2$ stimulated plant N demand more than microbial N mineralization as reflected by lower porewater $NH_4$ and higher root:shoot ratios (Figure 7). This pattern was non-linear in 2017 with a larger response at +5.1 $^0$C as we hypothesized, but not in 2018.

It should be noted that we were not able to test this hypothesis as stated because we were unable to satisfactorily measure N mineralization rates directly in this organic soil with very high root density. We are developing methods to overcome this limitation. However, interpreting the results as the balance between N plant demand and microbial N mineralization has proven to insightful for understanding the ecosystem-level treatment responses.

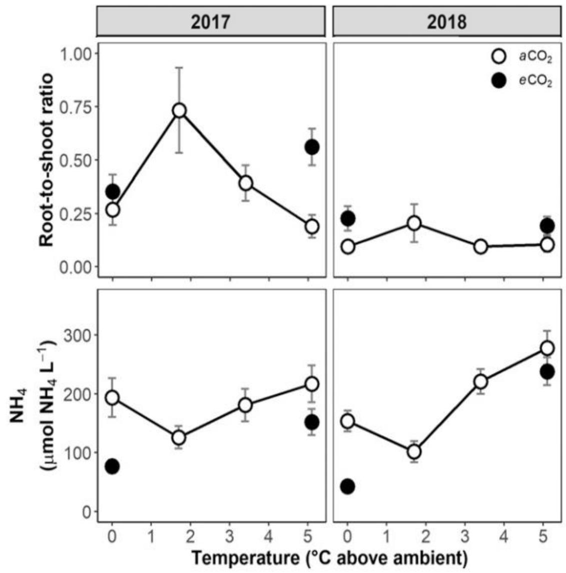


**Figure 7**. Changes in root:shoot ratio and porewater $NH_4$ in response to warming and *e*$CO_2$ in the C3 community. Circles are treatment means (n = 3) ± 1 SE; open circles are ambient $CO_2$ and closed are elevated $CO_2$.

**H3:** *The net effect of warming will be to increase carbon sequestration rates and marsh elevation in C3 and C4 communities initially, but this effect will decrease in magnitude through time. The interaction of warming and eCO₂ will be additive in the C3 community, but not in the C4 community.*

Elevation change is a integrating variable because it represents the net effect of net primary production gains in carbon mass and losses to decomposition and hydrologic export. Further, it is interpretable as soil carbon sequestration and tidal wetland resilience against sea level rise. We showed previously that soil elevation gain is driven primarily by root production, so we expected elevation gain would follow belowground responses to warming.

Our preliminary data support the hypothesis with respect to warming, with peak elevation gain at the lowest warming level +1.7 $^0$C where root growth was highest (Figure 8). However, the hypothesis was not supported in the *e*$CO_2$ treatments which caused a dramatic increase in belowground biomass but not a corresponding

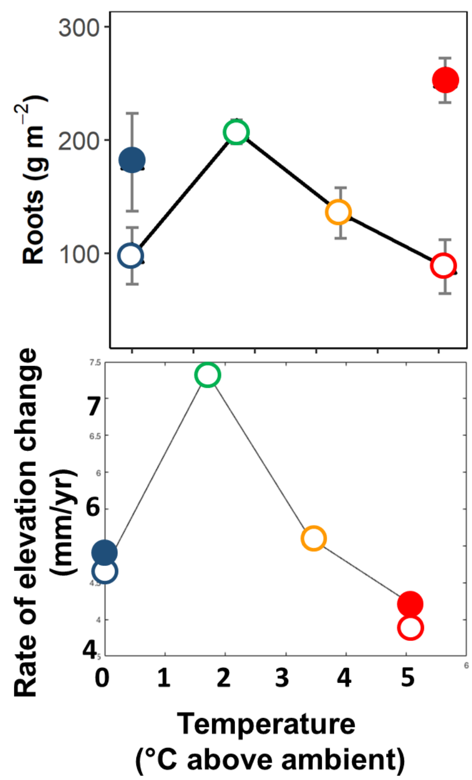


**Figure 8**. Root production and elevation responses to warming (open circles) and elevated $CO_2$ (closed circles).

increase in elevation (Figure 8). Our hypothesis to explain this divergence is that *e*$CO_2$ changes plant morphology in ways that increase $O_2$ transport into soils, stimulating aerobic microbial decomposition. Thus, both increases in production and decomposition offset one another leading to no net increase in soil carbon sequestration. We plan to test this hypothesis by measuring plant morphology, redox potential, nominal oxidation state of carbon, and plant metabolomics in collaboration with EMSL.

**C. Modeling Objectives:** Modeling objectives 3 and 4 mapped onto hypothesis 4 and are considered here in a single section.

**Objective 3:** ***Modify a well-established marsh carbon model to incorporate new insights gleaned from the warming experiment, including the impact of warming on productivity and decay, and potential interactions between inundation, warming, and elevated $CO_2$ that vary with plant species across real-life wetland landscapes.***

**Objective 4:** ***Migrate this refined marsh carbon model into the new wetland-enabled Community Land Model (CLM), producing the first attempt to capture tidal wetland dynamics in a fully prognostic land surface model with coupled water, energy, carbon and nutrient cycles.***

**H4:** *The positive impact of warming on carbon sequestration in marsh soils increases with inundation frequency and the rate of sea level rise. Enhanced sequestration will be greatest in the regularly flooded C3 community at the present elevation, but less in both the low-elevation C3 monolith treatment and the infrequently flooded C4 community.*

We proposed to test this hypothesis directly manipulating the elevation of soil monoliths in the treatment plots. However, we abandoned this treatment after engineering considerations showed the plan would interfere with the success of the soil warming treatments that we considered to be more important. To mitigate this change we focused on modeling elevation change in response to sea level rise and our treatments (Figure 9). Our modeling activity has been directed at understanding the *e*$CO_2$ effects and we are preparing to add warming effects.

Preliminary model runs indicate that *e*$CO_2$ confers a dramatic increase on marsh resilience to sea level rise (Figure 9). The

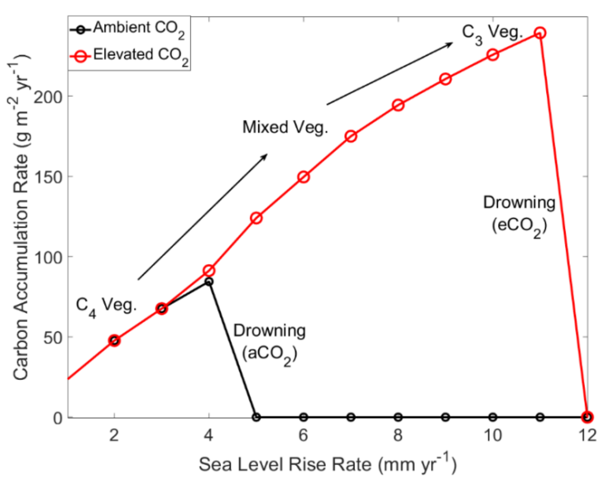


**Figure 9**. Results from model equilibration experiments in which a high elevation C4 marsh was subjected to progressively faster rates of sea level rise under ambient and elevated $CO_2$. Carbon accumulation rates (g $m^{-2}$ $yr^{-1}$) under ambient $CO_2$ (black open circles) and elevated $CO_2$ (red open circles) at sea level rise rates between 1 and 12 mm $yr^{-1}$, along with the average percent of C3 vegetation in the plot (blue line/open circles).

marsh drowns when sea level rise exceeds 4 mm $yr^{-1}$ under $a$$CO_2$ versus 11 mm $yr^{-1}$ under $e$$CO_2$. There is no effect of $e$$CO_2$ on carbon accumulation rate at low sea level rise rates because the marsh equilibrates to elevations too high for $C_3$ vegetation. Though we have not yet run warming experiments, the model supports our prediction of a relatively muted C4 community response to accelerated sea level rise (Figure 9). These model results were generated by modifications to the marsh carbon model developed by Co-PI Matt Kirwan.

We also made significant progress in development of PFLOTRAN coupled to ESM through the work of Co-PI Peter Thornton. We used long-term data sets from GCReW to parameterize the hydrology and vegetation. Tidal forcing is mimicked using a 2-column system initially designed for hummock-hollow microtopography in a peatland environment (Figure 10). In this new coastal implementation, one column simulates interactions between vegetation and soil while a second column simulates water level, both tidal and sea level rise. Based on simulations using this framework, we found that plant community responses to environmental change were non-linear, non-additive and inconsistent between C3 and C4 plants. We were able to characterize some of the shifts in root and shoot production observed at GCReW in response to temperature and $e$$CO_2$. However, we were more successful at characterizing C3 than C4 behavior. For C3 plants, the reparametrized model was able to predict the increase in total, root, and shoot NPP with $e$$CO_2$; peaks in root NPP and root:shoot ratio at moderate temperature increases (~2°C); and a synergistic effect of temperature and $e$$CO_2$ on total and root NPP and root:shoot ratio. For C4 plants, the model was able to capture the minimal effect of $e$$CO_2$ on growth and the minimal impact of both $e$$CO_2$ and temperature. However, the model was not successful at predicting C4 temperature trends. To remedy this situation, we manipulated the parameters that govern vegetation responses to identify the driving factors and determine what field measurements would be necessary to improve model performance, as well as biogeochemical processing that is currently absent from our simulations, but will have a significant impact on nutrient availability and vegetation dynamics.

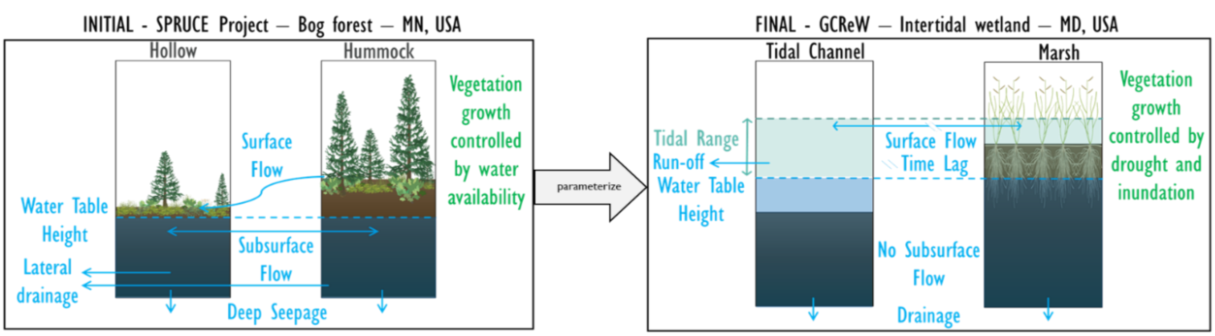


**Figure 10.** Initial 2-column structure available through the E3SM land model (ELM) and the final structure after parameterization to mimic saltmarsh conditions.

Incorporation of biogeochemistry is in development using PFLOTRAN. Previous work to couple PFLOTRAN and E3SM has been done for carbon diagenesis but has not incorporated a full redox ladder. At this stage, we have generated a soil profile that incorporates aerobic respiration, nitrification, denitrification, iron reduction, sulfate reduction, and methane production (Figure 11). Competition between plants and microbes has been incorporated by including nitrogen uptake rates based on rooting structure. Our biogeochemistry modelling goals are to: 1) use soil profile data to parameterize the soil column structure and reaction rates, 2) incorporate decomposition currently represented in E3SM with our parameterized redox reactions and 3) Update the ELM-PFLOTRAN interface to incorporate tracking of salinity, oxygen, root structure, and root biomass. To address our third biogeochemistry objective, we have fostered collaborations with Dan Ricciuto, Fengming Yuan, and Ben Sulman who will all be using the updated interface to incorporate biogeochemistry in terrestrial ecosystem simulations using ELM v1.1.

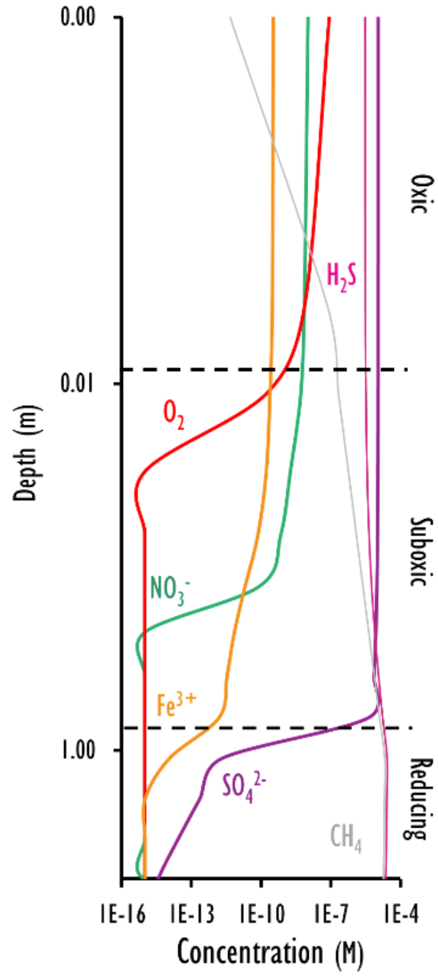


**Figure 11.** New redox representations in PFLOTRAN (log-log scale). Note there are more chemical species in the model than shown here.

**D. Temperature and Elevated $CO_2$ Effects on Methane Cycling**

We proposed to measure $CH_4$ emissions as one component of understanding changes in soil organic matter decomposition as stated in H2 but are reporting the results in this separate section because $CH_4$ dynamics allow us to infer processes that affect soil carbon sequestration.

Warming increased $CH_4$ emissions non-linearly, doubling at +5.1°C in both communities ($p<0.001$, Figure 12 inset; shows $C_3$ only). Gross primary production (GPP) also explained $CH_4$ flux variation at the $C_3$ site ($R^2$=0.22, $p<0.001$, Figure 12), but not the $C_4$ site (data not shown). This increase in $CH_4$ emissions is most simply explained as faster biochemical kinetics dictated by $Q_{10}$, accelerating fermentation of SOM to methanogenic electron donors (acetate and $H_2$). It is also possible that $CH_4$ production increased due to reduced competition with $SO_4$ reducers (see below). At the $C_3$ site, warming-enhanced GPP may have increased root exudates, accelerating all forms of heterotrophic microbial respiration.

Molecular oxygen ($O_2$) and $SO_4$ are the dominant electron-accepting compounds that suppress methanogenesis in SMARTX soils. Porewater data indicate that warming is stimulating $SO_4$ reduction (SR) because [$SO_4$] is lower than expected based on salinity (Figure 13). This is evidence that warming enhances the SR rate, but then the [$SO_4$] declines to the point that the process becomes $SO_4$-limited (Figure 11). GCReW porewater [$CH_4$] data suggest that $CH_4$ production increases under these conditions.

Interestingly, *e*$CO_2$ *decreased* $CH_4$ emissions at ambient ($p$=0.08) and +5.1°C ($p$=0.01, Figure 12 inset). Although either a decrease in $CH_4$ production and/or an increase in $CH_4$ oxidation could cause this pattern, there is circumstantial evidence to support an increase in aerobic $CH_4$ oxidation: (i) warming alone increased $CH_4$ emissions, and (ii) the *e*$CO_2$-driven reduction in $CH_4$ emissions was largest at +5.1°C, where *e*$CO_2$ increased belowground NPP the most (Figure 4). Anaerobic $CH_4$ oxidation is not a likely cause as rates should be positively related to [$SO_4$], and $SO_4$ depletion was similar at +5.1°C x ambient vs +5.1°C x *e*$CO_2$ ($p$=0.46, Figure 13). If correct, means that the net effect of higher shoot and root biomass is to increase $O_2$ diffusion into anaerobic soils, an effect with large implications for SOM decay rates.

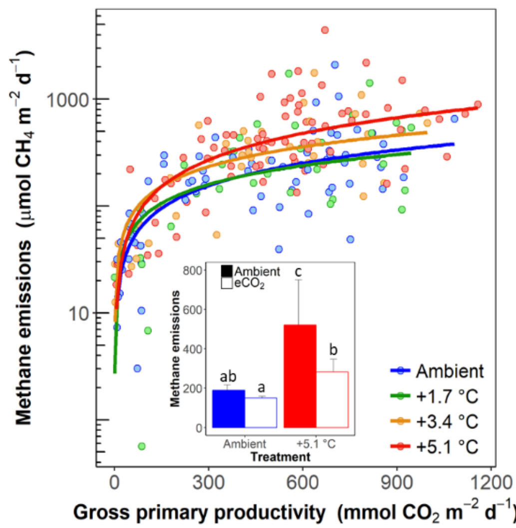


**Figure 12**. $C_3$ community $CH_4$ flux rose non-linearly with GPP and temperature (inset). *e*$CO_2$ suppressed $CH_4$ emissions (inset) despite higher NPP (Figure 4). The $C_4$ community had the same response.

### E. Microbial Carbon Use Efficiency

Perhaps the riskiest aspect of the proposal was our application of a novel position-specific $^{13}C$-tracer technique developed for aerobic systems to quantify carbon use efficiency in anaerobic ecosystems. The work was led by Dr. Paul Dijkstra with the goal of measuring the processes of energy production and biosynthesis using position-specific $^{13}C$-labeled metabolic tracers to understand how aerobic-anaerobic transitions change the processing of glucose as a function of temperature. This required developing new models for metabolic functioning that include gluconeogenesis and running experiments with fluctuating $O_2$ levels. Dr. Dijkstra succeed in the development of this new method and has one paper in preparation on the topic.

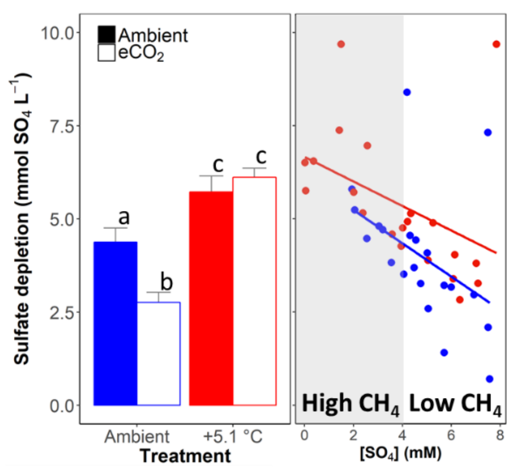


**Figure 13.** $SO_4$ depletion due to SR relative to the amount expected based on salinity. Left: mean of all depths. Warming caused more depletion due to more SR. Right: $SO_4$ depletion consumed $SO_4$ past a threshold where [$CH_4$] in porewater rose rapidly. Note lower [$SO_4$] with warming, and more depletion at a given [$SO_4$].

### F. Goals Not Met

We consider the grant a success because nearly all our goals were met. However, there were some challenges that changed the emphasis and direction of our proposal. The design and construction of the experiment was perhaps our biggest challenge because we proposed to do so in only 8 months in order to begin the study by May 1st and have three full years of data. We missed this deadline for the temperature treatment by four weeks, starting the experiment on Jun 1st of the first year. We missed the deadline for starting the elevated $CO_2$ treatment by one year, a strategic decision made in order to favor starting the more novel warming treatment. As a result, the first paper from the study by Noyce et al. (2019) reported two of the three years of data from this award because those were years with both temperature and *e*$CO_2$ treatments. These delays were necessary in order to design a robust experiment as described in section III.A and contributed to our goal of running the experiment long-term. One consequence of these delays is that we cannot separate the effects of starting the temperature treatment four weeks into the growing season from the fact that the first year was also unusually dry. We expect this to question to be resolved as we observe responses over more wet and dry years.

We decided not to implement the proposed manipulations of soil elevation designed to simulate the effects of sea level-driven flooding frequency. This decision was made to reserve space in the 4 $m^2$ subplots for sensors and future soil samples in the interest of the long-term operation of the experiment. We reasoned that questions about elevation change as it relates to sea level rise are ideal for model-based experiments, which were a major focus of the work (Figure 9).

Though Dr. Paul Dijkstra succeeded in developing a new method for using his position-specific 13C-tracer technique in anaerobic systems, it occurred at the end of the grant and we were not able to apply the method to the SMARTX experiment.

**IV. What Opportunities for Training and Professional Development**

Professional development is an important element of the mission of the Smithsonian Institution and of the Smithsonian Environmental Research Center. We define the term broadly to include all people who are building on a wide range of previous training to advance their careers, most of whom use their experiences to move onto opportunities outside of SERC. This grant provided professional development opportunities for students, interns, technicians destined for graduate school, career technicians, post-doctoral fellows, soft money-funded research scientists, and citizen scientists.

Dr. Roy Rich is the architect of the experimental system and led the project from design to construction. He was support on the grant full-time for the first year the transitioned to part-time (three months per year) for the second two years. The start provided by this grant led to a variety of new opportunities that allowed Dr. Rich to fund his Ecology and Technology Lab for the past five years.

Genevieve Noyce is supported on the grant as a Post-Doctoral Fellow of the Smithsonian Institution. With full-time support on this grant she has gained leadership skills and advanced to a Research Scientist position, making her a peer senior scientist. The grant allowed Dr. Noyce to build a reputation as a coastal wetland biogeochemist.

Teri O'Meara is a SERC Post-Doctoral Fellow based at ORNL with Peter Thornton. The grant allowed Dr. O'Meara to develop new modeling and coding skills, and expertise in E3SM and PFLOTRAN, leveraging her pre-existing expertise in marine biogeochemistry.

Ellen Herbert started as a Post-Doctoral Fellow at the Virginia Institute of Marine Science and transitioned to a permanent position at Ducks Unlimited as Director of the North American Research Program. Ellen has continued to be a collaborator on the research and publications in her new position.

Joshua Jones is a Post-Doctoral Fellow of the US Geological Survey where he is working with our collaborator Glenn Guntenspergen. Dr. Jones was supported by the USGS and led the measurements of soil organic matter decomposition rates. Dr. Jones transitioned into teaching biology at prestigious McDonogh High School.

Ten technicians with training ranging from undergraduate courses to completed MS degrees were supported to collect data and analyze samples. Here we provide a few examples of the outcome of this training. Anna Lienesch (MS) transitioned into a permanent position at NOAA, Janelle Whitman (BS) transitioned into a permanent position at a non-profit that promotes middle-school minority students into science careers, Evan Phillips (BS) remains at SERC but has been promoted, and Andrew Peresta (BS) is an African-American technician at SERC who was promoted into a permanent Federal position.

One graduate students were trained by the grant. David Nicks completed his MS thesis on the *response of* Spartina patens *and* Distichlis spicata *productivity to experimental sea-level rise* at the College of William and Mary.

Six undergraduate interns spend 12 weeks working on the project and performing independent studies. These were Sarah Freda (Bryn Mawr College), Charlie Mettler (Wabash College) and Jason Swartz (McDaniel College, under-represented). Audrey Geise (West Virginia University), Maya Bhalla-Ladd (Bryn Mawr College), and Helena Kleiner (Grinnell College). Four of these students are now in graduate school.

Approximately 30 volunteers assisted with the summer and fall census of plant biomass. Some of these people were undergraduate students majoring in science, but most were citizens interested in field research.

**V. Products**

**A. Presentations and Publications**

**1. Presentations**

Megonigal, J.P. 2016. Coastal Wetland Carbon Sequestration in a Warmer Climate. Global Change Research Wetland Symposium. Bryn Mawr College, Bryn Mawr, PA.

Megonigal, P., M. Kirwan, R. Rich, P. Dijkstra, P. Thornton, G. Guntenspergen, G. Noyce, E. Herbert, and J. Jones. 2016. Coastal Wetland Carbon Sequestration in a Warmer Climate. DOE TES-SBR Joint Meeting. Potomac, MD.

Megonigal, J.P. 2017. Global Change Impacts on Tidal Wetland Carbon Cycling. Oak Ridge National Laboratory (May 1st)

Megonigal, J.P. 2017. Plant-Microbe Interactions Regulate Greenhouse Gas Feedbacks to Global Change in a Model Tidal Marsh. Argonne National Laboratory (Mar 4th)

Megonigal, J.P. 2017. Plant-Microbe Interactions Regulate Greenhouse Gas Feedbacks to Global Change in a Model Tidal Marsh. University of Maryland Department of Plant Science and Landscape Architecture Lecture Series (Mar 16th)

Megonigal, J.P. 2016. Plant Traits and Sea Level Rise Dominate Tidal Marsh Response to Global Change. Joint NRE/EEB Seminar Series, University of Connecticut (Oct 28).

Noyce, G., P. Megonigal, M. Kirwan, R. Rich, P. Dijkstra, P. Thornton, G. Guntenspergen, E. Herbert, J. Jones. 2016. Coastal Wetland Carbon Sequestration in a Warmer Climate. AGU Annual Meeting (12 Dec).

Rich, R. 2017. Technology in support of ecological experiments. Ecology Seminar, University of Cork, Ireland (Apr).

Herbert, E., David Walters, Lisamarie Windham Myers, and Matthew Kirwan, 2017. Modeling carbon exchanges between bay, marsh and upland systems under accelerated sea level. Coastal and Estuarine Research Federation Biennial Meeting, Providence RI.

Megonigal, J.P. (Invited Lecture)**.** 2018. Washington College Environmental Science Honor Society. *Sea Level Rise and the Fate of Chesapeake Wetlands* (Mar 7$^{th}$)

Megonigal, J.P. (Public Lecture). 2018. Smithsonian Environmental Research Center Public Lecture Series. *Sea Level Rise and the Fate of Chesapeake Wetlands* (Jan 23rd)

Megonigal, J.P. (Seminar). 2018. University of Massachusetts. *Interactions Regulate Greenhouse Gas Feedbacks to Global Change in a Model Tidal Marsh* (Jan 31st)

Megonigal, J.P. (Seminar). 2018. Oak Ridge National Laboratory. *Global Change Impacts on Tidal Wetland Carbon Cycling* (May 1st)

Megonigal, J.P. (Seminar). 2018. Argonne National Laboratory. *Plant-Microbe Interactions Regulate Greenhouse Gas Feedbacks to Global Change in a Model Tidal Marsh* (Mar 4th)

Megonigal, J.P. (Seminar). 2018. Department of Plant Science and Landscape Architecture's Lecture Series, University of Maryland. *Plant-Microbe Interactions Regulate Greenhouse Gas Feedbacks to Global Change in a Model Tidal Marsh* (Mar 16th).

Kirwan, M. 2018. National Academy of Science workshop entitled Coastal Blue Carbon Approaches for Carbon Dioxide Removal and Reliable Sequestration, Woods Hole, MA. https://www.nap.edu/read/24965/chapter/1#7

**2. Publications**

Megonigal, JP, S Chapman, S Crooks, P Dijkstra, M Kirwan, A Langley. 2016. Impacts and effects of ocean warming on tidal marsh and tidal freshwater forest ecosystems. In: Laffoley, D, and Baxter, JM (editors). Explaining ocean warming: Causes, scale, effects and consequences. Gland, Switzerland: IUCN. pp. 105-122.

Megonigal JP, Chapman S, Langley A, Crooks S, Dijkstra P, Kirwan M. 2018. Coastal Wetland Responses to Warming. In: A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice, and Policy, Windham-Myers L-M, Crooks S, Troxler-Gann T (eds), CRC Press: Boca Raton, London, pp: 133-144.

Nicks, D.W., 2018. Response of *S. patens* and *D. spicata* productivity to experimental sea-level rise. Undergraduate thesis, College of William and Mary Department of Geology. 29 pp.

Schieder, N.W., Walters, D.C., and Kirwan, M.L., 2018. Massive upland to wetland conversion compensated for historical marsh loss in Chesapeake Bay, USA. Estuaries and Coasts 41, 940-951.

Noyce, G.L., M.L. Kirwan, R.L. Rich and J.P. Megonigal. 2019. Asynchronous nitrogen supply and demand produce non-linear plant allocation responses to warming and elevated $CO_2$. 116 (43): 21623-21628. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1904990116 (Appendix 1).

**B. Technologies**

The technology used to warm this ecosystem was transferred to other research programs in the U.S. and abroad, particularly a sister coastal marsh warming experiment in Hamburg, Germany and new facilities for elevated $CO_2$ research in wetlands based at the University of Cork, Ireland and the University of Dublin.

**VI. Impact**

Coastal wetlands are an extensive terrestrial-aquatic interface that dominate the coastal margins of continents and are global hotspots of carbon storage. Marshes, mangroves, and seagrass meadows account for about half of the total marine soil carbon budget and bury carbon equivalent to terrestrial forests despite occupying just 2.5% of Earth's land area. Despite the extraordinary leverage these ecosystems exert over the global carbon cycle, the dynamics of coastal wetlands are not presently represented in Earth system models. This experiment is affected the discipline by providing a direct test of hypotheses on tidal wetland responses to warming and funding the first efforts to include coastal wetlands in Earth system models. The interest generated by this work inspired research scientists to begin research programs at the coastal terrestrial-aquatic interface. In addition, the physical infrastructure supported by this award expanded the long-term capacity of the Smithsonian's Global Change Research Wetland to conduct cutting edge science and the technology we developed was transferred to research programs in Hamburg, Germany. Finally, the research informed a chapter on coastal marsh responses to warming published by the International Union for the Conservation of Nature in 2017 entitled *Explaining Ocean Warming: Causes, Scale, Effects and Consequences*. The IUCN is a non-profit organization with a global reach.