Final Report: Archiving Data to Support Data Synthesis of DOE Sponsored Elevated CO_2 Experiments

J. Patrick Megonigal

Report to DOE-TES Program on Grant DE-SC0008339
5 September 2017

Executive Summary

Over the last three decades DOE made a large investment in field-scale experiments in order to understand the role of terrestrial ecosystems in the global carbon cycle, and forecast how carbon cycling will change over the next century. The Smithsonian Environmental Research Center received one of the first awards in this program and managed two long-term studies (25 years and 10 years) with a total of approximately $10 million of support from DOE, and many more millions leveraged from the Smithsonian Institution and agencies such as NSF. The present DOE grant was based on the premise that such a large investment demands a proper synthesis effort so that the full potential of these experiments are realized through data analysis and modeling. The goal of the this grant was to archive legacy data from two major elevated carbon dioxide experiments in DOE databases, and to engage in synthesis activities using these data. Both goals were met.

All datasets deemed a high priority for data synthesis and modeling were prepared for archiving and analysis. Many of these datasets were deposited in DOE's CDIAC, while others are being held at the Oak Ridge National Lab and the Smithsonian Institution until they can be received by DOE's new ESS-DIVE system at Berkeley Lab. Most of the effort was invested in researching and re-constituting high-quality data sets from a 30-year elevated CO_2 experiment. Using these data, the grant produced products that are already benefiting climate change science, including the publication of new coastal wetland allometry equations based on 9,771 observations, public posting of dozens of datasets, metadata and supporting codes from long-term experiments at the Global Change Research Wetland, and publication of two synthetic data papers on scrub oak forest responses to elevated CO_2. In addition, three papers are in review or nearing submission reporting unexpected long-term patterns in ecosystem responses to elevated CO_2 and nitrogen in a coastal wetland.

Report

I. Accomplishments

A. Objectives

Over the last three decades DOE made a tremendous investment in field-scale experiments in order to understand the role of terrestrial ecosystems in the global carbon cycle, and forecast how carbon cycling will change over the next century. The Smithsonian Environmental Research Center received one of the first awards in this program and managed two long-term studies (25 years and 10 years) with a total of approximately $10 million of support from DOE, and many more millions leveraged from the Smithsonian Institution and agencies such as NSF. The present DOE grant was based on the premise that such a large investment demands a proper synthesis effort so that the full potential of these experiments are realized through data analysis and modeling.

The Smithsonian Environmental Research Center (SERC) was the led institution of two studies sponsored by DOE's Terrestrial Carbon Process Program. One of these (Scrub Oak) ended in 2007, while the other (Coastal Wetland) is ongoing. Collectively, these experiments produced over a hundred publications and 35 years of field observations. Nearly all of the data from these experiments were stored in electronic files and subjected to quality reviews before publication of the results, and metadata were available for many of the files. However, the data hae not been organized and archived in a fashion that facilitates data synthesis and modeling, particularly for exercises designed to integrate data across experiments.

The goal of the work performed by this grant was to archive legacy data from two experiments, make the data publically available, and use these data in cross-site synthesis activities, leading to publications.

B. Accomplishments

Task 1: The first task was to archive data from the Scrub Oak experiment, with priority given to datasets needed for the synthetic modeling exercise led by Dr. Anthony Walker of Oak Ridge National Lab (Table 1). Most of the datasets were relatively complete, but significant effort was invested in preparing the meteorological data for the inter-model comparison study. Assembled meteorological datasets were transferred to the ORNL team for additional refinement before they were used to parameterize several forest-scale biogeochemical model. Datasets deposited in CDIAC were developed by Bruce Hungate (table 1).

Table 1. Summary of the high priority data sets collected from the Scrub Oak experiment over 10 years that were archived in task 1.

Data Set	**Data Set Name**	**Address or Disposition**
Scrub Oak Site Meteorological Data	Clean Meteo Data.xlsx	Sent to ORNL; Waiting for ESS-DIVE
Inside Chamber Meteorological Data	Chamber Data.xlsx	Sent to ORNL; Waiting for ESS-DIVE
Soil Water Content Data	SICO2_FL_soil_water.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Aboveground Biomass & Growth	SICO2_FL_Aboveground_Diameter_Density_Biomass.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Belowground Production (Ingrowth)	SICO2_FL_Belowground_biomass_C_ N_15N.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Belowground Biomass (GPR and Harvest)	SICO2_FL_Belowground_biomass_C_ N_15N.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Leaf Area Index	Model_initialisation and	Sent to ORNL; Waiting for ESS-DIVE

Table 1. Summary of the high priority data sets collected from the Scrub Oak experiment over 10 years that were archived in task 1.		
Data Set	**Data Set Name**	**Address or Disposition**
	parameterisation needed.xlsx	
Soil carbon and nutrients	SICO2_FL_Soil_C_N_15N_mineral_CPOM_density_fractions.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Deep soil carbon, nutrients, trace metals	SICO2_FL_Soil_C_N_15N_mineral_CPOM_density_fractions.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Allometric equations of oak species	SICO2_FL_Aboveground_Diameter_Density_Biomass.xlsx	ftp://cdiac.ornl.gov/pub/FACE/kscdata/
Net Ecosystem Exchange	Seasonal NEE.xlsx	Sent to ORNL; Waiting for ESS-DIVE
Water Table	Model_initialisation and parameterisation needed.xlsx	Sent to ORNL; Waiting for ESS-DIVE
Soil respiration	Rs chamber summary.xlsx	Sent to ORNL; Waiting for ESS-DIVE

Task 2: The second task was be to archive data sets from the marsh experiment (Table 2), giving priority to datasets that are most useful for synthesis and modeling. Although the data from this experiment had been maintained in electronic formats and synthesized as late as 2007 (Erickson et al. 2007), we discovered a large number of methodological inconsistencies and errors that led us to review all of the data in detail. Because about 75% of the data had already been published, we also performed a detailed comparison of the impact of these errors on past results. All of the research was thoroughly documented and archived, providing a detailed account of the decisions we made for future investigators. This activity accounted for the majority of the effort from the post-doctoral associate on the grant (Meng Lu) because of the meticulous approach we adopted.

Table 2. Summary of the high priority data sets collected from the Coastal Wetland experiment over 30 years that were archived in task 2.		
Data Set	**Data Set Name**	**Address or Disposition**
Total Shoot Density and Biomass	CO2xComm Total Shoot Biomass 1987-2013	https://serc.si.edu/gcrew/CO2data
Total Root Production	CO2xComm Total Root Biomass 1987-2013.xls	https://serc.si.edu/gcrew/CO2data
Root Production by Category	CO2xComm Root Biomass by Category 2000-2013.xls	https://serc.si.edu/gcrew/CO2data
Grass and Non-Sedge Density & Biomass	CO2xComm Non-Sedge Shoot Biomass.xls	https://serc.si.edu/gcrew/CO2data
Sedge (*Scirpus*) Density & Biomass	CO2xComm Sedge Shoot Biomass 1987-2013.xls	https://serc.si.edu/gcrew/CO2data
Sedge (*Scirpus*) Density	CO2xComm Master SC Density 1987-2013(08-21-2015).xls	https://serc.si.edu/gcrew/CO2data
Sedge (*Scirpus*) Dimensions	CO2xComm Master SC Census 1987-2013 (08-21-2015).xls	https://serc.si.edu/gcrew/CO2data
Sedge (*Scirpus*) Allometry	CO2xComm Master Harvest 1987-2013 (08-21-2015).xls	https://serc.si.edu/gcrew/CO2data
Grass & Non-Sedge Biomass & Density	CO2xComm Master C4 Harvest 1987-2013 (08-21-2015).xls	https://serc.si.edu/gcrew/CO2data

Root Ingrowth Core Mass	CO2xComm Master Root 1987-2013 (08-21-2015) .xls	https://serc.si.edu/gcrew/CO2data
Shoot C, 13C, N, 15N Content	CO2xComm Master Shoot CN 1987-2014 (08-21-2015) .xls	https://serc.si.edu/gcrew/CO2data
Root C, 13C, N, 15N Content	CO2xComm Master Root CN 1987-2014 (08-21-2015) .xls	https://serc.si.edu/gcrew/CO2data
Porewater Chemistry	CO2xComm Porewater (2002-2013) .xls	https://serc.si.edu/gcrew/CO2data
Meteorological Data	GCREW Meteorological Data (1986-2013).xls	https://serc.si.edu/gcrew/CO2data

Task 3: The final task was to engage in two synthesis activities using the assembled data sets. The first of these was a model inter-comparision of several terrestrial elevated CO_2 experiments, including the Scrub Oak experiment. The Post-Doctoral research associate (Dr. Meng Lu) and I participated in a three day workshop titled *Model-Experiment Synthesis of Terrestrial Ecosystem Responses to Elevated CO_2*, provided data interpretation, and contributed to a publication that is presently in review.

The second activity was met through three strategies: (1) analyzing the newly assembled data to produce a variety of synthetic products, (2) analyzing the data to detect previously hidden long-term patterns, and (3) making the data publically available for use in synthetic analyses by other research groups. Here I report on the outcome of each strategy.

1. The newly assembled data supported by this grant allowed efficient analysis by code, and the following new analyses:

(i) We performed a detailed analysis of 8,430 allometric measurements made on individual stems of the dominant sedge *Schoenoplectus americanus* over 30 years of treatment. Allometry is used to estimate plant biomass because it is not destructive, which minimizes long-term damage to our experimental plots. This unprecedented dataset allowed us to determine the influence of elevated CO_2 treatment, nitrogen availability, climate and time on the allometric relationship of biomass to plant dimensions (height, width). We found that none of these factors had a significant effect on the allometric relationship, which meant that a single equation applies to all the plant growth data collected over 30 years. The full dataset, metadata, allometric equations and statistical data for *S. americanus* and 10 other common tidal marsh species was published as a Data Paper in *Ecology* in 2016.

(ii) Use of a single allometric equation applied across all years, treatments and replicates helped improve our biomass estimates. In the past, a different allometric equation calculated from 10 or fewer stems was applied to each plot in each year. Because our analysis of 8,430 stems shows that allometry is constant across all plots and years, the previous approach introduced variation into biomass estimates. Furthermore, we streamlined the procedures used for our annual biomass estimates by eliminating the work of harvesting plants for allometric relationship determinations.

(iii) In addition to an improved estimate of sedge biomass, we incorporated biomass data for the other species that occur in these plots. Because the initial focus of the 30-year experiment was to compare the responses of sedge versus grass species, the data on other species was never put into electronic files, nor had calculations of whole-plot biomass been performed. The new structure of the data allowed us to calculate the 30-year history of total biomass, which we are presently preparing as a second Data Paper for *Ecology*.

2. The grant supported the assembly of aboveground and belowground biomass response data, but also a variety of other data such as tissue and porewater chemistry. Particularly important was the effort to assemble the data on tissue N content and isotope ratios. Analyses of the new datasets has produced at least two synthetic papers that are being prepared for publication at present.

(i) We discovered that the well-documented increase in primary productivity and stem density caused by elevated CO_2 over 30 years was accompanied a phenomena of *shrinking stems*. Elevated CO_2 has caused the stem diameter and height of the dominant species *S. americanus* to become smaller over time. We hypothesize that denser stems were associated with the expansion of roots and rhizomes to alleviate N limitation, as evidenced by decreased N immobilization in living tissue and litter, high tissue C:N, and low available porewater nitrogen. Changes in tissue chemistry and morphology reversed upon N addition, supporting our hypothesis. We showed that morphological adaptations to CO_2 and N supply alter competitive interactions, key ecosystem services, and the capacity of marshes to build elevation against rising sea levels. This work is in preparation for submission to *Nature*.

(ii) We learned that the plant community response to elevated CO2 has changed dramatically over the 30 year period, and that there has been no CO_2 stimulation observed within the last 5 years. This pattern cannot be explained by changes in N availability or temperature, but it was explained by changes in sea level. The elevated CO_2 response of *S. americanus* shoot biomass and density followed a sigmoidal relationship sea level. The recent decline in response appears associated with the increase in sea level during this period. Overall, these data indicate that sea level rise suppresses the expected increase in plant productivity, with possible consequences for soil carbon sequestration and elevation gain expected from elevated CO_2 alone. This insight into tidal wetland responses to elevated CO_2 has important implications for models of marsh stability in the face of accelerated sea level rise.

3. An important goal was to make the 30 years of tidal marsh elevated CO_2 experimental data publically available for synthetic analyses by other research groups. These data have not been

deposited in CDIAC because we learned that CDIAC was being replaced by ESS-DIVE. The data will be transferred to ESS-DIVE in fall 2017; in the meantime, all of these data are posted on the Smithsonian Institution website where it can be freely downloaded. The Data Page of the Global Change Research Wetland provides data, metadata and codes for "raw" (i.e. all collected data processed only for quality control) and "derived" datasets (required code-driven calculation using one or more raw datasets). We also posted the code so the system is transparent.

The posted data has already produced a synthetic publication that is in press in Ecology Letters under the title *Asynchrony Among Local Communities Stabilizes Ecosystem Function at Larger Spatial Scales*. The work applied a theoretical framework to 62 datasets on plant species abundance and 33 datasets on primary productivity to assess the mechanisms that confer plant community stability at multiple hierarchical levels. We found that changes in plant community composition are not synchronized across local communities, and that this dramatically lowers temporal variability across large spatial scales. The work is evidence that maintaining meta-community heterogeneity helps to stabilize ecosystem services, and shows the potential

Goals Not Met

Most of the goals set out in the proposal were met. As expected, not every available dataset was archived. This was anticipated because of limited time and resources, and the need to focus on data needed for synthetic activities. The original proposal classified the datasets into high and low priority depending on the extent to which the data were needed for modeling or synthesis. We archived all the high priority datasets, but not the low priority datasets. That said, many of the lower priority datasets are available in publications, and are therefore available for further research.

C. Opportunities for Training and Professional Development

Most of the resources in this grant supported of Dr. Meng Lu, a Post-Doctoral Associate. Dr. Lu has one first-authored paper from the work and several other papers that are nearing submission. Through this support, Dr. Lu attended and gave presentations at several ESA Annual Meetings and three Global Change Research Wetland Symposia. He also received training in Geographic Information Systems, SAS coding, and R coding.

D. Dissemination of Results

The results were presented at professional meetings, published in peer-reviewed journals. Data were posted in both CDIAC and a publically accessible Smithsonian Institution website.

III. Products

A. Presentations and Publications

i. Presentations

Seminar: Oak Ridge National Laboratory. *Global Change Impacts on Tidal Wetland Carbon Cycling* (1 May 2017; JPM)

Seminar: Argonne National Laboratory. *Plant-Microbe Interactions Regulate Greenhouse Gas Feedbacks to Global Change in a Model Tidal Marsh* (4 Mar 2017; JPM)

Seminar: 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* (16 Mar 2017; JPM).

Speaker: 4th Global Change Research Wetland Symposium, Smithsonian Environmental Research Center, MD. *Shrinking stems of marsh plant under elevated carbon dioxide*. (10 Mar 2017; ML).

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

Speaker: ESA Annual Meeting, Fort Lauderdale, FL. *Shrinking stems of marsh plant under elevated carbon dioxide*. (8 Aug 2016; ML).

Seminar: M. Gordan Wolman Seminar, Johns Hopkins University. *Tidal Marsh Stability in a Future Climate* (17 Feb 2017; JPM).

Speaker: Smithsonian Environmental Research Center Seminar Series. *Responses of marsh plant biomass allocation to elevated CO_2: A case study at Chesapeake Bay*. (22 Oct 2016; ML).

Seminar: Rosenberg Institute. Title: *Global Change Impacts on Wetland Vulnerability to Sea Level Rise* (2 Sep 2015; JPM).

Speaker: ESA Annual Meeting, Baltimore, MD. *Responses of marsh plant biomass allocation to elevated CO_2: A case study at Chesapeake Bay*. (12 Aug 2015; ML).

Seminar: Chesapeake Biological Laboratory. Title: *Global Change Impacts on Wetland Vulnerability to Sea Level Rise* (1 Oct 2014; JPM).

Invited Lecture: Smithsonian Institution *Anthropocene: Life in the Age of Humans* series. Title: *Coastal Legacies*. (Nov 2014; JPM).

Seminar: University of Delaware. Title: *Global Change Impacts on Wetland Vulnerability to Sea Level Rise* (14 Apr 2014; JPM).

Keynote Speaker: Estuarine and Wetland Research Graduate School of Hamburg Final Conference. University of Hamburg (25 Oct 2014; JPM).

Invited Speaker: Shell Gabon Community Seminar. Title: The Smithsonian's Marine Global Earth Observatory network (3 Apr 2014; JPM).

Seminar: Virginia Commonwealth University. Title: *Global Change Impacts on Wetland Vulnerability to Sea Level Rise* (9 Sep 2014; JPM).

ii. Publications

Lu M, JA Langley, ER Herbert and JP Megonigal. In preparation. Shrinking stems of marsh plants under elevated carbon dioxide. (scheduled to be submitted to *Nature* in Sep 2017).

Zhu, C, LH Ziska, AJ Langley, M Lu, JP Megonigal. In preparation. After 30 years, rising sea level negates carbon dioxide stimulation of elevation gain in a Chesapeake tidal wetland. (scheduled to be submitted to *Nature* in Dec 2017).

Nelson, N, R Muñoz-Carpena, P.J. Neale, M Tzortziou, JP Megonigal. 2017. Temporal variability in the importance of hydrologic, biotic, and climatic descriptors of dissolved oxygen dynamics in a shallow tidal-marsh creek. *Water Resources Research*. 53, doi:10.1002/2016WR020196.

Pastore, MA, JP Megonigal, and JA Langley. 2017. Elevated CO_2 and nitrogen addition accelerate net carbon gain in a brackish marsh. 133:73-87. *Biogeochemistry*. DOI 10.1007/s10533-017-0312-2

Lu, M, JS Caplan, JD Bakker, JA Langley, TJ Mozdzer, BG Drake, JP Megonigal. 2016. Allometry data and equations for coastal marsh plants. *Ecology* 97(12): 3554-3554

Morris, JT, DC Barber, JC Callaway, R Chambers, SC Hagen, CS Hopkinson, BJ Johnson, P Megonigal, SC Neubauer, T Troxler, and C Wigand. 2016. Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. *Earth's Future*. 4. doi:10.1002/2015EF000334.

Hungate, BA, FP Day, P Dijkstra, BD Duval, CR Hinkle, JA Langley, JP Megonigal, P Stiling, DW Johnson and BG Drake (2013). Fire, hurricane and carbon dioxide: effects on net primary production of a subtropical woodland. *New Phytologist*. doi: 10.1111/nph.12409

Hungate,BA, P Dijkstra, Z Wu, BD Duval, FP Day, DW Johnson, JP Megonigal, ALP Brown, JL Garland (2013). Cumulative response of ecosystem carbon and nitrogen stocks to chronic CO_2 exposure in a subtropical oak woodland. *New Phytologist*, doi: 10.1111/nph.12333

B. Technologies

Nothing to report.

IV. Participants and Other Collaborating Organizations

A. Individuals

1. J. Patrick Megonigal. Smithsonian Environmental Research Center (Principle Investigator). One month per year of effort for project period supported by the Smithsonian Institution. No collaborations with foreign countries.

2. Meng Lu. Smithsonian Environmental Research Center (Post-Doctoral Fellow). Twelve months of effort per year for project period supported by this grant. Dr. Lu maintains collaborations in his home country of China.

3. Bert Drake. Smithsonian Environmental Research Center (Emeritus Scientist). One week of effort total with no institutional support. No collaborations with foreign countries.

4. John Erikson. University of Florida (Professor).

One week of effort total with support from his home institution. No collaborations with foreign countries.

5. Gary Peresta. Smithsonian Environmental Research Center (Engineer).
One week of effort total with support from the Smithsonian Environmental Research Center. No collaborations with foreign countries.

6. Andrew Peresta. Smithsonian Environmental Research Center (Engineer).
One week of effort total with support from the Smithsonian Environmental Research Center. No collaborations with foreign countries.

7. Joshua Caplan. Bryn Mawr College.
One month of effort total with support from his home institution. No collaborations with foreign countries.

8. Jonathan Bakker. University of Washington.
One month of effort total with support from his home institution. No collaborations with foreign countries.

9. Adam Langley. Villanova University.
One month of effort total with support from his home institution. No collaborations with foreign countries.

10. Tom Mozdzer. Bryn Mawr College.
One month of effort total with support from his home institution. No collaborations with foreign countries.

V. Impact

The project made available to the public the world's longest dataset on ecosystem responses to elevated CO_2, supported a unique cross-site inter-model comparison, and uncovered long-term patterns in elevated CO_2 responses that are relevant to managing coastal wetlands.

VI. Changes and Problems

The amount of effort required to reconstruct several 30-year datasets required more time than anticipated, and meant that we archived only those datasets deemed essential for modeling and synthesis.