Data-model synthesis of grassland carbon metabolism:

Quantifying direct, indirect & interactive effects of warming & elevated CO_2

DOE Award Number: SC0006973

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Contributing members: Dana Blumenthal took over for Jack Morgan upon his retirement as the USDA-ARS PI. This DOE grant supported three postdocs: Jane Zelikova (UW), Claudia Boot (CSU), and Edmund Ryan (ASU). The postdocs were provided with mentoring related to career development, team building and collaboration, in addition to detailed scientific/intellectual advice. The DOE-TES grant supported the PHACE data manager, Samantha Ewers, as well as several undergraduate or postgraduate technicians, including Jeffrey Stinson, Bailey Terry, Austin Steel, Jennifer Bell, Mark Schimelpfenig.

This report contains no patentable material or protected data.

3. Executive Summary:

This research project improved understanding of how climate change (elevated atmospheric CO2, warming and altered precipitation) can affect grassland ecosystem productivity and nutrient availability. Our advanced experimental and modeling methods allowed us to test 21 specific hypotheses. We found that ecosystem changes over years of exposure to climate change can shift the plant communities and potentially make them more resilient to future climate changes. These changes in plant communities may be related to increased growth of belowground roots and enhanced nutrient uptake by some species. We also found that climate change can increase the spread of invasive and noxious weeds. These findings are important for land managers to make adaptive planning decisions for domestic livestock production in response to climate variability in semi-arid grasslands.

4. Goals, Objectives and Actual Accomplishments

Our original objectives were to:

1) Characterize "fast" processes underlying diurnal to seasonal dynamics of C metabolism components, as driven by soil moisture, temperature, substrate and nutrient availability, plant activity, root and microbial activity, and root-microbe feedbacks such as priming.
2) Characterize "slow" processes underlying interannual and long-term (>5 yr) dynamics of C metabolism components, as driven by precipitation variability, plant community composition, and nutrient status.
3) Evaluate and inform the representation of these slow and fast processes in ESMs by applying hierarchical Bayesian data-model assimilation methods.

We have accomplished all of these goals, as evidenced by numerous publications related to each goal. One key outcome of our work is that future climate conditions may enhance soil organic matter decomposition, which could further aggravate climate change. This is explained by community-scale plant and microbial traits interacting at the root-soil interface, through adjustments in microbial community composition and exoenzyme stoichiometric balance that result from plant responses to climate change and disturbance. These adjustments are likely to depend upon changes in N availability, which appears to regulate the extent of organic matter decomposition.

We also found that a deep-rooted, invasive forb becomes very competitive under elevated CO_2, as its rapid growth and less conservative water use allowed it to increase its biomass several-fold. Additionally, a fast-growing annual invasive grass increased dramatically with warming. These findings have important implications for management of invasive weeds with climate change, which may become more dominant in future conditions.

Over slower time scales, we found that grassland production was stabilized under elevated CO_2 conditions, but dominant grasses declined in production while other less abundant grasses increased. This means that the grassland ecosystem became more resilient to variable precipitation conditions. The growing season for grazing ecosystems was extended by the combination of elevated CO_2 and warming, because of water saving due to reduced stomatal conductance. In practical terms, these findings are relevant for ranchers and land managers as they plan their grazing activities and on a broader scale, grassland production stability can be useful for predicting carbon uptake and sequestration.

Our project has also resulted in development of improved modules in a widely used ecosystem simulation model, DayCent, and has allowed Bayesian data-model assimilation methods to be applied to fast fluxes and isotopic composition for partitioning respiration into autotrophic and heterotrophic components. (See Section 7 for more details).

5. Summarize project activities for the entire period of funding

5.1 Our original hypotheses are organized around our objectives and specific aims:

Objective 1. Characterize "fast" processes underlying diurnal to seasonal dynamics of C metabolism components, as driven by soil moisture, temperature, substrate and nutrient availability, root and microbial activity, and root-microbe feedbacks such as priming.

Specific aim 1.1: Quantify responses of GPP, leaf-level photosynthesis and stomatal conductance to environmental drivers and PHACE treatments.

H1.1a: Stimulation of GPP by elevated CO_2 is due primarily to increased soil water.
H1.1b: Suppression of GPP by warming is due primarily to reduced soil water content.
H1.1c. Leaf photosynthetic responses to elevated CO_2 and warming will primarily be controlled by soil water availability through hydraulic regulation of stomatal conductance, and secondarily through alterations of plant carbon source-sink balance and N availability.
H1.1d. Aboveground plant respiration will be enhanced by warming, but its temperature sensitivity will be controlled by water availability, and secondarily by CO_2 treatment.
H1.1e: Incorporating biochemical-based C_3 and C_4 photosynthesis submodels into DayCent will improve predictions of NPP and GPP.

Specific aim 1.2: Quantify responses of Re, R_s, R_h and R_p to environmental drivers and PHACE treatments.

H1.2a: Stimulation of Re by elevated CO_2 is due to combined effects of increased SWC and enhanced R_h.
H1.2b: Suppression of Re by warming is due primarily to reduced SWC.

H1.2c: Across treatments, enhanced R_h is associated with increased belowground labile C availability and root production.
H1.2d: Elevated CO_2 and warming interact to alter R_p, with interactions explained by SWC.
H1.2e: Mechanistic understanding of belowground CO_2 production, CH_4 consumption, and gaseous transport is necessary to capture temporal dynamics of respiration components in response to precipitation inputs.

Specific aim 1.3: Link aboveground and belowground controls on ecosystem C metabolism.

H1.3a: Priming provides a critical link between fast-time scale belowground processes related to R_h and decomposition and fast-time scale processes related to photosynthesis and C allocation.
H1.3b: Inclusion of a priming mechanism into ecosystem models such as DayCent will improve predictions of R_h and thus R_e and NEE.
H1.3c: Temporal and spatial partitioning of R_h and R_p can be facilitated by physical models of CO_2 transport that incorporate microbial, rhizosphere, priming, and environmental influences on CO_2 production.

Objective 2. Characterize "slow" processes underlying interannual and long-term (>5 yr) dynamics of C metabolism components, as driven by precipitation variations, plant community composition, and nutrient status.

Specific aim 2.1. Investigate interactive effects between interannual variations in the timing and amount of precipitation and PHACE treatments on ecosystem C metabolism.

H2.1a: Response of GPP to elevated CO_2 and warming varies with spring precipitation amount.
H2.1b: Compensatory effects of elevated CO_2 and warming on R_e vary with spring precipitation amount.
H2.1c: C fluxes following precipitation pulses constitute a significant portion of the annual C budget.

Specific aim 2.2. Assess effects of changes in plant community composition (defined by C_3 and C_4 biomass) resulting from PHACE treatments on ecosystem C metabolism.

H2.2a: The relative abundance of C_3 and C_4 species does not affect GPP.
H2.2b: The relative abundance of C_3 and C_4 species affects R_h due to differences in litter quality.

Specific aim 2.3. Quantify long-term (>5 years) PHACE treatment effects on nutrient availability and subsequent effects of altered nutrients on C metabolism.

H2.3a: N availability will not decline in elevated CO_2 treatments within the study period due to enhanced moisture content and priming of SOM decomposition.
H2.3b: N and P availability will increase in warmed treatments due to enhanced mineralization and/or reduced uptake.
H2.3c: N depletion will occur over much longer time periods (e.g., decade to centuries), resulting in productivity declines over long time periods.

5.2 Approaches:

This grant provided partial support for the Prairie Heating and CO2 Enrichment (PHACE) project, which was initiated in 2005, with final harvest taking place in summer, 2013. Funding from DOE allowed us to evaluate carbon and nutrient cycling in the context of climate change in native and disturbed grasslands, to improve simulation models, and to conduct data-model synthesis activities. Biomass harvests took place at peak season in mid- to late-July of each year. Soil coring for belowground biomass, microbial community composition and physiology, and biogeochemical properties took place immediately after aboveground harvest, and processing of soil and root samples took several months to a year following harvest. Carbon cycling in the field was measured using a canopy gas exchange system and traditional static trace gas chambers, combined with stable isotope analysis. Additional experiments were conducted in growth chambers and greenhouses to test biogeochemical mechanisms underlying the “fast” ecosystem responses observed in the field. “Slow” ecosystem responses that manifested over 5 years or longer were observed by comparing time courses of biomass growth by species and vegetation greenness, and by conducting modelling experiments over decadal to century time scales. Fortunately we had no major issues with any of the methods we planned to use.

5.3 Summary of Key Findings:

We were able to demonstrate that plant-soil feedbacks mediate climate change effects on grassland C metabolism; antecedent conditions and plant activity are important in regulating ecosystem respiration; and stoichiometry of N:P in the rhizosphere is altered by climate change with potential longer-term consequences for ecosystem sustainability. Improved understanding of the importance of prior environmental conditions in regulating ecosystem C metabolism resulted from our novel data-model synthesis approach. Details of our findings are available in our peer-review journal articles and book chapters, and a few Research Highlights are included here.

5.4 Research Highlights

5.4.1. Precipitation controls responses of ecosystem phenology to elevated CO_2 and warming in a semi-arid grassland (Jane Zelikova et al. 2015, Journal of Ecology)

We used time series repeat photography to examine how elevated CO_2 and temperature affect the cover of dominant grasses, whole plant community phenology, and the potential for carbon uptake (as indicated by plot greenness) (Zelikova et al. 2015; Fig. 6). Warming generally enhanced plant cover development and greenness early in the growing season, but was detrimental later in the growing season, when water was limiting. Elevated CO_2 had a similarly positive effect on plant cover and greenness development in the middle of the growing season and at times, we saw an additive effect of warming and elevated CO_2 in combination. Finally, plant cover and greenness responses to elevated CO2 were large in the first two years, and decreased thereafter, suggesting acclimation to elevated CO_2. In contrast, plant greenness and cover in warmed plots continued to respond to warming throughout the eight year experiment. The greenness data have been important in modeling ecosystem carbon and water fluxes in response to climate change (Ryan et al. 2015; and Ryan et al. in review).

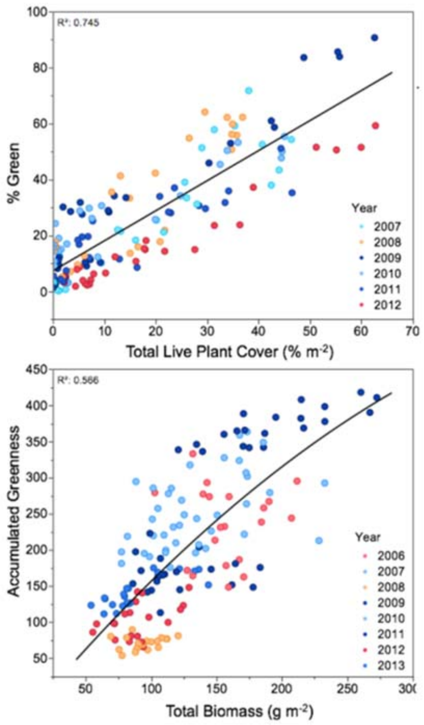

Figure 1. Greenness as derived from HSV in digital repeat photographs at PHACE, as a function of total live plant cover and biomass (Zelikova et al. 2015).

5.4.2. Antecedent moisture and temperature conditions modulate the response of ecosystem respiration to elevated CO_2 and warming (Ryan et al. 2015, Global Change Biology)

We synthesized six years (2007-2012) of ecosystem respiration (R_{eco}) data from the Prairie Heating and CO_2 Enrichment (PHACE) experiment. We applied a semi-mechanistic temperature-response model to evaluate the response of R_{eco} to three treatment factors (elevated CO_2, warming, and soil water manipulation) and their interactions with antecedent conditions (e.g., past soil water content [SWC] and soil temperature [SoilT]) and aboveground factors (e.g., vapor pressure deficit, photosynthetically active radiation, vegetation greenness). The model fit the observed R_{eco} well ($R^2 = 0.77$). We applied the model to estimate annual (March – October) R_{eco}, which was stimulated under elevated CO_2 in most years, partly due to the indirect effect of elevated CO_2 on SWC (Figure 2). When aggregated from 2007-2012, total six-year R_{eco} was stimulated by elevated CO_2 singly (24%) or in combination with warming (28%). Warming had little effect on annual R_{eco} under ambient CO_2, but stimulated it under elevated CO_2 (32% across all years) when precipitation was high (e.g., 44% in 2009, a "wet" year). Treatment-level differences in R_{eco} can be partly attributed to the effects of antecedent (past) SoilT and vegetation greenness on the temperature sensitivity of R_{eco}, and to the effects of antecedent and current SWC and vegetation activity (greenness modulated by VPD) on R_{eco} base rates. Thus, this study indicates that the incorporation of both antecedent environmental conditions and aboveground vegetation growth are critical to predicting R_{eco} now and in a future climate of elevated CO_2 and warming.

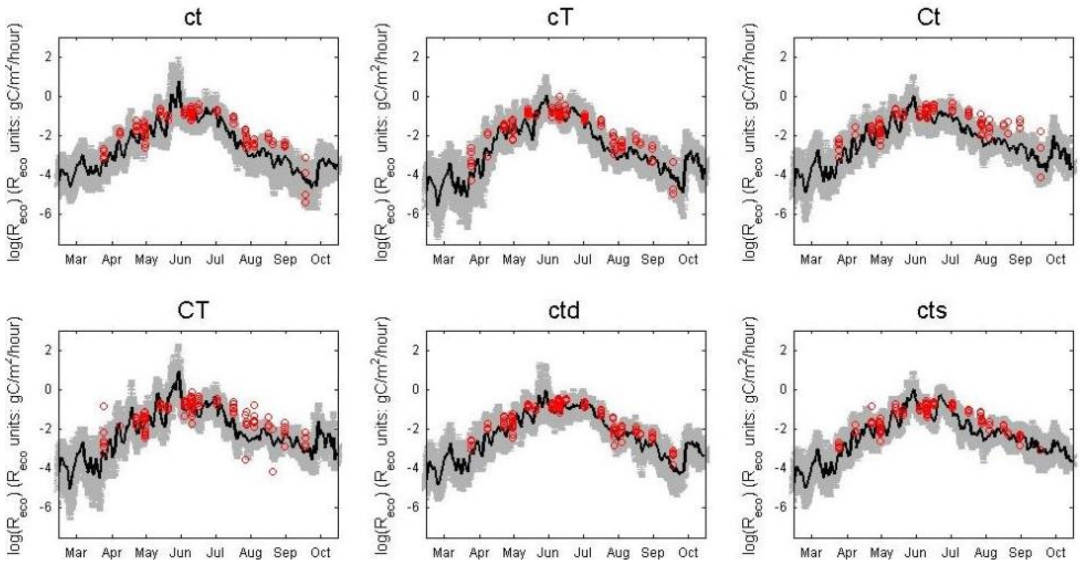

Figure 2. Time series of predicted log(R_{eco}) for each treatment in 2009, represented by the posterior means for the daily values (black line) and central 95% credible intervals on the hourly time-scale (grey region). The red circles denote observations of log(R_{eco}). Treatment codes: ct, ambient CO2 and temperature; cT, warmed; Ct, elevated CO2; CT, elevated CO2 and warmed; ctd, deep irrigation; cts, shallow irrigation.

5.4.3. Mediation of soil C decomposition by arbuscular mycorrizhae in grass rhizospheres under elevated CO_2 (Yolima Carrillo et al. 2015, Biogeochemistry)

Using field soils under controlled conditions we empirically tested the hypothesis that decomposition (measured as rhizosphere C priming) would increase with elevated CO_2 due to greater plant-derived labile C, and arbuscular mycorrhyzae (AM) would further enhance this effect due to AM ability to promote decomposition in the short-term. We also hypothesized that the degree of control by AM of the response to elevated CO_2 would vary with grass species, as C_3 and C_4 grasses would vary in the strength of their mutualisms with AM. Results support that AM can mediate suppressive effect (negative priming) of elevated CO_2 on soil C decomposition in the rhizosphere of a C3 grass, a potential mechanism explaining variation in impacts of eCO_2 on soil C storage (Figure 3; also see Carrillo et al. 2014).

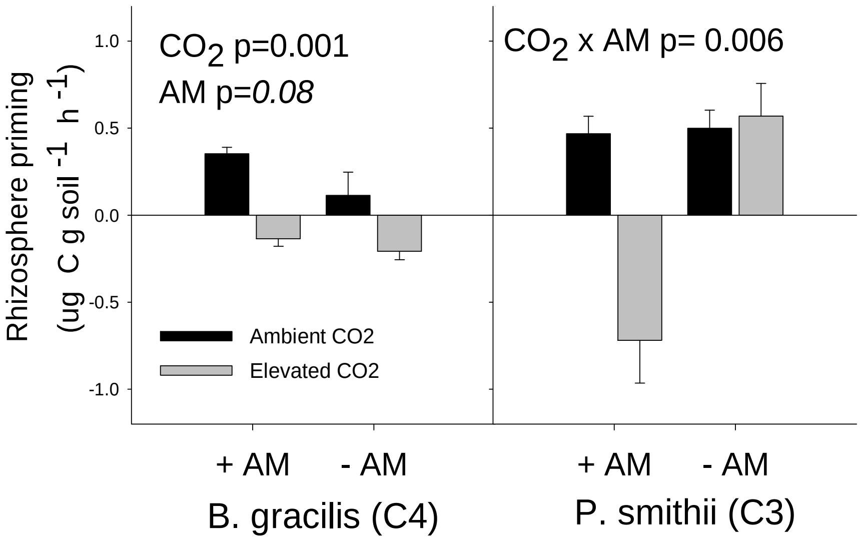

Figure 3. Rhizosphere priming of soil organic matter-derived C in soil planted with *Bouteloua gracilis* and *Pascopyrum smithii* exposed to ambient and elevated CO_2 and +AM and -AM treatments. Priming calculated as difference between planted and unplanted pots, with positive and negative values indicating enhancement and inhibition of SOM decomposition, respectively. Values are least square means with standard error (n=4) from ANCOVA controlling for soil water effects on CO_2 production. p values also from ANCOVA.

5.4.4. Rhizosphere Priming Effects Enhance Plant Nitrogen Availability Under Elevated CO_2 (Nie & Pendall, in revision, Agriculture, Ecosystems and Environment).

Rhizosphere priming has been shown to mediate decomposition of soil organic matter (SOM), but little is known about its effects on plant N availability, which may promote sustainable plant growth under elevated CO_2 (eCO_2). By using ^{13}C and ^{15}N labeling, we investigated priming of SOM decomposition and its relationship with plant N availability of C4 (*Bouteloua gracilis*) and C3 (*Hesperostipa comata*) grasses under eCO_2. We observed that eCO_2 induced increases in plant biomass, plant N availability, rhizosphere priming, and overall SOM decomposition in both species. Increased overall SOM decomposition was positively related with plant N availability of both C4 and C3 grasses under eCO_2. However, C3 grass was more dependent on N acquired from rhizosphere priming of SOM than C4 grass. Our findings highlight that plant N availability could be enhanced under eCO_2 via accelerated SOM decomposition.

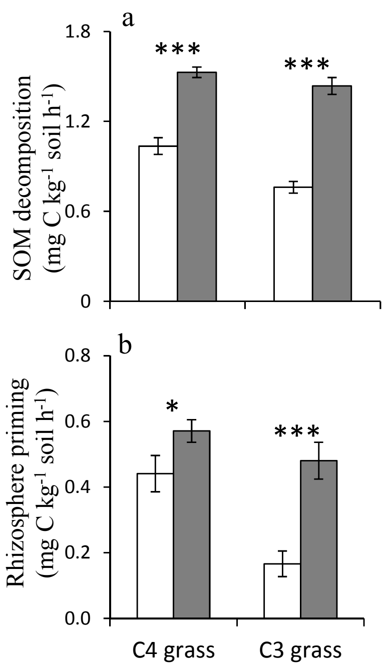

Figure 4. Overall SOM decomposition (a) and rhizosphere priming of SOM decomposition (b). Values are given as mean ± standard error (n = 5). Statistically significant differences between ambient and elevated CO_2 are marked by asterisks: t-test, one asterisk, $P < 0.05$; two asterisks, $P < 0.01$; three asterisks, $P < 0.001$.

6. Products

6.1. Journal Articles & Book Chapters (published or in press),

1. Bell, C., Y. Carrillo, C. M. Boot, J. D. Rocca, E. Pendall and M. D. Wallenstein (2014). Rhizosphere stoichiometry: are C : N : P ratios of plants, soils, and enzymes conserved at the plant species-level? New Phytologist 201: 505-517. DOI: 10.1111/nph.12531.
2. Blumenthal, D. M. and J. A. Kray (2014). Climate change, plant traits, and invasion in natural and agricultural ecosystems. . Invasive species and global climate change. L. H. Ziska and J. S. Dukes. Wallingford, U.K., CABI Press.
3. Blumenthal, D. M., J. A. Kray, W. Ortmans, L. H. Ziska and E. Pendall (in press). Cheatgrass is favored by warming but not CO_2 enrichment in a semi-arid grassland. Global Change Biology. DOI:
4. Blumenthal, D. M., V. Resco, J. A. Morgan, D. G. Williams, D. R. LeCain, E. M. Hardy, E. Pendall and E. Bladyka (2013). Invasive forb benefits from water savings by native plants and carbon fertilization under elevated CO_2 and warming. New Phytologist 200: 1156-1165. DOI: 10.1111/nph.12459.
5. Brzostek, E., J. M. Blair, J. S. Dukes, S. D. Frey, S. E. Hobbie, J. Melillo, R. J. Mitchell, E. Pendall, P. B. Reich, G. R. Shaver, A. Stefanski, M. Tjoelker and A. C. Finzi (2012). The effect of experimental warming and precipitation change on proteolytic enzyme activity: positive feedbacks to nitrogen availability are not universal. Global Change Biology 18: 2617-2625. DOI: 10.1111/j.1365-2486.2012.02685.x.
6. Carrillo, Y., F. A. Dijkstra, D. LeCain, J. A. Morgan, D. Blumenthal, S. Waldron and E. Pendall (2014). Disentangling root responses to climate change in a semiarid grassland. Oecologia 175: 699-711. DOI: 10.1007/s00442-014-2912-z.
7. Carrillo, Y., F. A. Dijkstra, D. LeCain and E. Pendall (2015). Mediation of soil C decomposition by arbuscular mycorrizhal fungi in grass rhizospheres under elevated CO_2. Biogeochemistry 127: 45-55. DOI: 10.1007/s10533-015-0159-3.
8. Carrillo, Y., F. A. Dijkstra, E. Pendall, D. LeCain and C. Tucker (2014). Plant rhizosphere influence on microbial C metabolism: the role of elevated CO_2, N availability and root stoichiometry. Biogeochemistry 117: 229-240. DOI: 10.1007/s10533-014-9954-5.
9. Carrillo, Y., F. A. Dijkstra, E. Pendall, J. A. Morgan and D. M. Blumenthal (2012). Controls over Soil Nitrogen Pools in a Semiarid Grassland Under Elevated CO_2 and Warming. Ecosystems 15: 761-774. DOI: 10.1007/s10021-012-9544-0.
10. Carrillo, Y., E. Pendall, F. A. Dijkstra, J. A. Morgan and J. M. Newcomb (2011). Response of soil organic matter pools to elevated CO_2 and warming in a semi-arid grassland. Plant and Soil 347: 339-350. DOI: 10.1007/s11104-011-0853-4.

11. Chen, J., Y. Carrillo, E. Pendall, F. A. Dijkstra, R. Evans, J. Morgan and D. G. Williams (2015). Soil microbes compete strongly with plants for soil inorganic and amino acid nitrogen in a semiarid grassland exposed to elevated CO2 and warming. Ecosystems 18: 867-880. DOI: 10.1007/s10021-015-9868-7.
12. Chen, J., T. J. Zelikova, E. Pendall, J. A. Morgan and D. G. Williams (2015). Daily and seasonal changes in soil amino acid composition in a semiarid grassland exposed to elevated CO2 and warming. Biogeochemistry 123: 135-146. DOI: 10.1007/s10533-014-0057-0.
13. Dijkstra, F. A., Y. Carrillo, E. Pendall and J. A. Morgan (2013). Rhizosphere priming: a nutrient perspective. Frontiers in Microbiology 4. DOI: 10.3389/fmicb.2013.00216.
14. Dijkstra, F. A., J. A. Morgan, R. F. Follett and D. R. Lecain (2013). Climate change reduces the net sink of CH4 and N2O in a semiarid grassland. Global Change Biology 19: 1816-1826. DOI: 10.1111/gcb.12182.
15. Dijkstra, F. A., E. Pendall, J. A. Morgan, D. M. Blumenthal, Y. Carrillo, D. R. LeCain, R. F. Follett and D. G. Williams (2012). Climate change alters stoichiometry of phosphorus and nitrogen in a semiarid grassland. New Phytologist 196: 807-815. DOI: 10.1111/j.1469-8137.2012.04349.x.
16. LeCain, D., D. Smith, J. Morgan, B. A. Kimball, E. Pendall and F. Miglietta (2015). Microclimatic Performance of a Free-Air Warming and CO2 Enrichment Experiment in Windy Wyoming, USA. Plos One 10. DOI: 10.1371/journal.pone.0116834.
17. Morgan, J. A., D. R. LeCain, E. Pendall, D. M. Blumenthal, B. A. Kimball, Y. Carrillo, D. G. Williams, J. Heisler-White, F. A. Dijkstra and M. West (2011). C-4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. Nature 476: 202-U101. DOI: 10.1038/nature10274.
18. Nie, M., C. Bell, M. D. Wallenstein and E. Pendall (2015). Increased plant productivity and decreased microbial respiratory C loss by plant growth-promoting rhizobacteria under elevated CO2. Scientific Reports 5. DOI: 10.1038/srep09212.
19. Nie, M., M. Lu, J. Bell, S. Raut and E. Pendall (2013). Altered root traits due to elevated CO2: a meta-analysis. Global Ecology and Biogeography 22: 1095-1105. DOI: 10.1111/geb.12062.
20. Nie, M., E. Pendall, C. Bell, C. K. Gasch, S. Raut, S. Tamang and M. D. Wallenstein (2013). Positive climate feedbacks of soil microbial communities in a semi-arid grassland. Ecology Letters 16: 234-241. DOI: 10.1111/ele.12034.
21. Nie, M., E. Pendall, C. Bell and M. D. Wallenstein (2014). Soil aggregate size distribution mediates microbial climate change feedbacks. Soil Biology & Biochemistry 68: 357-365. DOI: 10.1016/j.soilbio.2013.10.012.
22. Ogle, K. and E. Pendall (2015). Isotope partitioning of soil respiration: A Bayesian solution to accommodate multiple sources of variability. Journal of Geophysical Research-Biogeosciences 120: 221-236. DOI: 10.1002/2014jg002794.

23. Parton, W. J., M. P. Gutmann, E. R. Merchant, M. D. Hartman, P. R. Adler, F. M. McNeal and S. M. Lutz (2015). Measuring and mitigating agricultural greenhouse gas production in the US Great Plains, 1870-2000. Proceedings of the National Academy of Sciences of the United States of America 112: E4681-E4688. DOI: 10.1073/pnas.1416499112.
24. Parton, W. J., J. A. Morgan, D. Smith, S. del Grosso, L. Prihodko, D. R. LeCain, R. Kelly and S. M. Lutz (2012). Impact of precipitation dynamics on net ecosystem productivity. Global Change Biology 18: 915-927. DOI:
25. Pendall, E., J. L. Heisler-White, D. G. Williams, F. A. Dijkstra, Y. Carrillo, J. A. Morgan and D. R. LeCain (2013). Warming Reduces Carbon Losses from Grassland Exposed to Elevated Atmospheric Carbon Dioxide. Plos One 8. DOI: 10.1371/journal.pone.0071921.
26. Reeves, J. L., D. M. Blumenthal, J. A. Kray and J. D. Derner (2015). Increased seed consumption by biological control weevil tempers positive CO2 effect on invasive plant (Centaurea diffusa) fitness. Biological Control 84: 36-43. DOI.
27. Reyes-Fox, M., H. Steltzer, M. J. Trlica, G. S. McMaster, A. A. Andales, D. R. LeCain and J. A. Morgan (2014). Elevated CO2 further lengthens growing season under warming conditions. Nature 510: 259-+. DOI: 10.1038/nature13207.
28. Ryan, E. M., K. Ogle, T. J. Zelikova, D. R. LeCain, D. G. Williams, J. A. Morgan and E. Pendall (2015). Antecedent moisture and temperature conditions modulate the response of ecosystem respiration to elevated CO2 and warming. Global Change Biology 21: 2588-2602. DOI: 10.1111/gcb.12910.
29. Suseela, V., D. Triebwasser-Freese, N. Linscheid, J. A. Morgan and N. Tharayil (2014). Litters of photosynthetically divergent grasses exhibit differential metabolic responses to warming and elevated CO2. Ecosphere 5. DOI: 10.1890/es14-00028.1.
30. Tucker, C. L., J. Bell, E. Pendall and K. Ogle (2013). Does declining carbon-use efficiency explain thermal acclimation of soil respiration with warming? Global Change Biology 19: 252-263. DOI: 10.1111/Gcb.12036.
31. Zelikova, T. J., D. M. Blumenthal, D. G. Williams, L. Souza, D. R. LeCain, J. Morgan and E. Pendall (2014). Long-term exposure to elevated CO2 enhances plant community stability by suppressing dominant plant species in a mixed-grass prairie. Proceedings of the National Academy of Sciences of the United States of America 111: 15456-15461. DOI: 10.1073/pnas.1414659111.
32. Zelikova, T. J., D. G. Williams, R. Hoenigman, D. M. Blumenthal, J. Morgan and E. Pendall (2015). Seasonality of soil moisture mediates responses of ecosystem phenology to elevated CO2 and warming in a semi-arid grassland. Journal of Ecology 103: 1119-1130. DOI: 10.1111/1365 2745.12440.

6.2 Journal Articles & Book Chapters (in review),

1. Ryan, E., et al. Gross primary production responses to warming, elevated CO2, and irrigation: quantifying the drivers of ecosystem physiology in a semi-arid grassland. In review at New Phytologist.
2. Ogle, K., et al. Quantifying and reducing uncertainties in soil trace gas fluxes with hierarchical data-model integration. In review at JGR- Biogeosciences.
3. Mueller, K., et al. Impacts of warming and elevated CO2 on a semiarid grassland are non-additive, shift with precipitation, and reverse over time. In review at Ecology Letters.
4. Nie, M and Pendall, E. Do rhizosphere priming effects enhance plant nitrogen uptake under elevated CO2? In revision at Agriculture, Ecosystems and Environment.

6.3 Presentations

1. Blumenthal, D.M. Global change, water, and invasion in a semi-arid grassland. Presented at NeoBiota, Ponte Vedra Spain, September 2012.
2. Blumenthal, D.M. Follow the water, Global change and plant invasion in a semi-arid grassland. Ecology, Evolution and Conservation Biology seminar series. Reno, NV, November 2012.
3. Blumenthal, D.M. Follow the water, Global change and plant invasion in a semi-arid grassland Department of Ecology, and Evolutionary Biology. Boulder, CO, December 2012.
4. Blumenthal, D.M. Rangeland Resources Research Unit - A short history of favorite discoveries. USDA-ARS Resource Day, Fort Collins, CO, February 2013.
5. Parton WJ. Ecosystem Response of Great Plains Grasslands to Climate Variability, Soil Science Society of America Annual Meeting, October 2012.
6. DelGrosso SD, Parton WJ, Morgan JA. DayCent Simulated Impact of the PHACE Climatic Change Experiments. Soil Science Society of America Annual Meeting, October 2012.
7. Parton WJ. Environmental Change in the US Great Plains Grasslands, linking experimental Results , Ecosystem Models and Regional Model Predictions. To be presented at the CLIMANI-INTERFACE Workshop, Scaling Climate Change Experiments Across Space and Time, Challenges of Informing Large-Scale Models with small-scale Experiments, in Mikulov, Czech Republic (June 2013).
8. Bell CW, Calderon C, Pendall E, Wallenstein MD. Plant rhizosphere species-specific stoichiometry and regulation of extracellular enzyme and microbial community structure. American Geophysical Union Fall Meeting, San Francisco CA, December 2012.
9. Pendall E, Carrillo Y, Heisler-White J, Dijkstra FA, Morgan JA, Williams DG, Wallenstein MD. Carbon cycling in a native grassland exposed to elevated CO2 and warming, A role for priming. Ecological Society of America Annual Meeting, Aug 4-9 2012, Portland OR.

10. Sorokin Y, Pendall E, Brennan A, Williams DG. Responses of evapotranspiration to experimental warming and elevated CO2 in a semi-arid grassland. Ecological Society of America Annual Meeting, Aug 4-9 2012, Portland OR.
11. Nie M, Bell J, Raut S, Pendall E. Responses of root morphology and function to elevated CO2 in terrestrial ecosystems, a meta-analysis. Ecological Society of America Annual Meeting, Aug 4-9 2012, Portland OR.
12. Hopkins FM; Brennan AL; Pendall E. Long term temperature sensitivity of soil carbon pools in a prairie warming experiment. American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 4-9, 2012.
13. Carrillo Y; Dijkstra FA; Pendall E; LeCain DR; Morgan JA. Experimental Evidence Linking Elevated CO2, Rhizosphere C/N Stoichiometry and Microbial Efficiency. American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 4-9, 2012.
14. Brennan AL; Pendall E; Risk DA; Carrillo Y. Continuous soil respiration at the Prairie Heating and Elevated CO_2 site using forced diffusion chambers. American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 4-9, 2012.
15. Pendall E, Invited seminar, Terrestrial ecosystem feedbacks to climate change, Example from Wyoming grassland. Department of Geology, Stockholm University, Sweden. 23 Jan 2013.
16. Pendall E, Invited seminar, Unexpected carbon cycle climate feedbacks, the importance of rhizosphere mechanisms. University of Western Sydney, Australia. 30 May 2013.
17. Boot CM, Wallenstein MA, Pendall E. Climate Effects on the Chemical Composition of Dissolved Organic Matter in Grassland Soil Porewater. Goldschmidt Geochemistry Conference, Sacramento, CA, June 2014.
18. Carrillo, Y ,Bell, C., Boot, C., Koyama, A., Rocca, J., Wallenstein, M., Pendall, E. Linking rhizosphere environments with C decomposition in-situ. Ecological Society of America Annual Meeting, 2014, Sacramento, CA.
19. Carrillo, Y. Pendall E. Dijkstra, FA. LeCain D. Elevated CO2 and arbuscular mycorrhizal abundance interact to regulate soil C decomposition in the rhizosphere of a C3 (but not a C4) grass American Geophysical Union, Annual Meeting 2013, San Francisco, CA.
20. Dijkstra, FA, Carrillo, Y.; Pendall, E, Morgan JA. Rhizosphere priming: a nutrient perspective. American Geophysical Union, Annual Meeting 2013, San Francisco, CA.
21. Mueller K, Blumenthal D, LeCain DR, Pendall E, Effects of elevated CO_2 and warming on plant productivity, soil moisture, and plant water-relations in a semi-arid grassland. American Geophysical Union (AGU) Fall Meeting, San Francisco, CA. 2014.
22. Nelson L, Raut S, Zelikova TJ, Williams DG, Pendall E. Belowground carbon cycling after six years of Prairie Heating and CO_2 Enrichment: Decomposition of C_3 & C_4 grass roots and soil organic matter. Ecological Society of America Annual Meeting, Sacramento, CA, August 2014.

23. Nie M and Pendall E. Beneficial bacteria alleviate progressive nitrogen limitation under elevated CO_2, American Geophysical Union Fall Meeting 2013, San Francisco, CA. 2013.
24. Ogle K. Ecological synthesis in an era of big data: Multi-scale synthesis of plant and ecosystem functioning from deserts to forests, Department of Biology, University of Florida, Gainesville, FL. 2014.
25. Ogle K. Exogenous and endogenous controls on soil carbon efflux in arid and semi-arid ecosystems, Department of Soil & Crop Sciences Seminar Series, Colorado State University, Ft. Collins, CO. 2013
26. Ogle K. Exogenous and endogenous controls on soil carbon efflux in arid and semi-arid ecosystems, Department of Botany, University of Wyoming, Laramie, WY. 2013.
27. Ogle K, *E. Ryan*, F. Dijkstra, E. Pendall. A hierarchical modeling approach to estimating soil trace gas fluxes from static chambers. American Geophysical Union (AGU) Fall Meeting, San Francisco, CA (poster). 2014.
28. Ogle K, E. Ryan, E. Pendall. Acclimatization of the temperature sensitivity of ecosystem respiration: Synthesis of a 5-year global change experiment, American Geophysical Union (AGU) Fall Meeting, San Francisco, CA (talk). 2013.
29. Pendall E, Sanderman J, Baldock J, Hovenden M. Soil Organic C Storage Under Elevated CO_2 is Dependent on Plant Species: A Role for C Quality? Goldschmidt Geochemistry Conference, Sacramento, CA, June 2014.
30. Pendall E and Nie, M. Altered precipitation dampens ecosystem C sequestration. American Geophysical Union Fall Meeting 2013, San Francisco, CA. 2013.
31. Pendall E, Carrillo Y, Nie M, Osanai Y, Nelson L, Sanderman J, Hovenden M, Baldock J. Root Mediation of Soil Organic Matter Feedbacks to Climate Change. American Geophysical Union Fall Meeting, San Francisco, CA. 2014.
32. Richards J, Blumenthal D, Pendall E, Williams DG. Comparison of local and non-local taxa in grassland restoration under future climate conditions. Society for Ecological Restoration. 2013.
33. Ryan E. A synthesis of the long-term responses of ecosystem respiration to altered temperature, moisture and atmospheric CO_2. School of Mathematical and Statistical Sciences, Arizona State University, Tempe, AZ. 2013.
34. Ryan, E., K. Ogle,_D. Peltier, D.G Williams, E. Pendall. Gross primary production of a semiarid grassland is enhanced by six years exposure to atmospheric CO_2, warming, and irrigation. American Geophysical Union (AGU) Fall Meeting, San Francisco, CA (poster). 2014.
35. Ryan E, K. Ogle, E. Pendall. A synthesis data-model integration of the 5-year response of ecosystem respiration to altered temperature, moisture and atmospheric CO_2, American Geophysical Union (AGU) Fall Meeting, San Francisco, CA (poster). 2013.

36. Susseela, V., Tharayil N, Pendall E. Characterizing the changes in biopolymer composition in roots of photosynthetically divergent grasses exposed to future climates. American Geophysical Union Fall Meeting 2014, San Francisco, CA. 2014.
37. Ryan, E. Invited talk. Statistical and mathematical approaches to understanding the factors governing ecosystem Carbon fluxes. Department of Mathematics and Statistics Colloquium, Northern Arizona University, Flagstaff, AZ, fall 2014.
38. Ogle, K. Invited talk. Ecological memory of plant and ecosystem processes spanning multiple time-scales. Department of Ecology and Evolutionary Biology Seminar, University of California, Irvine, CA, Spring 2015.
39. Ogle, K. Invited talk. Ecological memory of plant and ecosystem processes spanning multiple time-scales. Department of Ecology and Evolutionary Biology Seminar, Columbia University, New York, NY, Fall 2015.

7. Modeling & Synthesis Activities

7.1 DayCent Simulations of Carbon and Water Fluxes: Dr. Bill Parton

The Colorado State University portion of the project focused on using the DayCent model to simulate the impact of elevated CO2 and warming on ecosystem dynamics for the Short Grass Steppe, and evaluating the impact of grazing level, precipitation events, live plant biomass and satellite derived NDVI on Net Carbon Exchange for the Short Grass system. The first paper (Assessing the Ecological Impact of UV Radiation on Decay of Surface Litter using the DayCent Model, Chen, Parton, Gao, and Adair) describes the ability of the DayCent model to simulate the impact of UV radiation on surface litter decay and the observed seasonal patterns in daily NEE, AET and soil water for the CPER short grass steppe site from 2001-2003. Model optimization techniques were used to determine best fit plant growth parameters (photosynthesis and plant growth parameters) based on the observed daily NEE, AET and soil water data sets. The paper is written and will be submitted for publication to Ecosphere in March 2016.

The second paper (Simulated Impact of Elevated CO2 and warming on Ecosystem Dynamics for the Short Grass Steppe Grassland, DelGrosso, Parton, Morgan) is being written currently and shows environmental change impacts on plant production, soil carbon , and trace gas fluxes. The paper presents DayCent model predictions of the impact of elevated CO2 and warming on ecosystem dynamics for the Colorado Short Grass Steppe site and compares the simulated model results with the observed data from the PHACE project. Results from this effort have been presented at several national scientific meetings and will be submitted for publication during 2016.

We are also working on a paper which describes the impact of observed changes in the climate during the last 100 years on ecosystem dynamics for the Great Plains. This paper shows the historical changes in temperature and precipitation during the last century for the

Great Plains and DayCent simulated model results. DayCent simulated the impact of climatic changes and land use patterns on plant production, soil carbon, trace gas fluxes and system carbon during the last 100 years. The model results show that during dry periods plant production and system C decreases, while soil C increases. Wet periods cause plant production and system carbon to increase, while soil carbon decreases. The model results show that there were large losses of greenhouse gasses from 1900 to 1930 as a result of plowing of grasslands in the Great Plains. The paper was published in PNAS during 2015 (Parton et al 2015).

Parton et al (2012) published a paper which described the impact of precipitation on net ecosystem carbon exchange(NEE) using daily observed NEE data from different grazing treatments from a site in Eastern Colorado. The results showed that spring precipitation and soil water contents are the primary factors which control NEE dynamics with most of the net carbon uptake and growth of live biomass occurring during the April to June time period. The results also showed that microbial heterotrophic respiration was greatly enhanced for two days following precipitation events. We developed a regression model that simulated daytime and nighttime NEE as a function of live biomass , soil water content, rainfall events, and solar radiation and is able to predict daily NEE during the April to October growing season($r2= 0.72$).The major factors which control NEE dynamics are the observed live biomass and soil water content(0-20 cm depth). We are currently using a revised version of this regression model to simulate the growing season NEE from the Colorado SGS site from 1982 to 2014 using observed satellite NDVI and simualted soil water data from the DayCent model as inputs into regression equation model. We are using the observed seasonal changes in NDVI to determine seasonal patterns in live biomass (live biomass is highly correlated to NDVI ($r2=0.9$)). We are currently writing a paper which describes the results from this effort which will be submitted for publication to Ecosphere during 2016.

We are also have written a paper which evaluated the impact of seasonal change in precipitation and grazing intensity on NEE for the SGS Short Grass Steppe site in Eastern Colorado using data from 2001 to 2006 . The results show that most of the net ecosystem carbon uptake occurs during the April to June time period, that low precipitation in the spring greatly reduces live biomass and NEE, and that heavy grazing decreases net carbon uptake during the April to June time period and increases carbon losses during the fall and winter time periods. We are currently revising the paper (Morgan et al, in prep) in accordance with review comments and will resubmit the paper for publication by the end of March 2016.

7.2 Bayesian modeling of PHACE data: Dr. Kiona Ogle, Dr. Edmund Ryan, Dr. Elise Pendall

We have developed and implemented several Bayesian models that allowed us to synthesize multiple datastreams from the PHACE experiment in novel ways. These analyses are also contributing to our development of the fast-time scale soil C cycle model, DETECT (see next section).

Ecosystem respiration (Reco) analysis

We developed a simple ecosystem CO_2 efflux (or respiration) (i.e. Reco) model that we fit to Reco data and associated micromet and soil environmental data within a hierarchical Bayesian framework. This analysis allowed us to evaluate (1) how Reco is responding to the six different treatments of PHACE and (2) how current and past (antecedent) soil water and soil temperature affect Reco and its response to elevated CO_2 and warming. We used a modified version of the Lloyd and Taylor model (Lloyd & Taylor, 1994) the analyzed the Reco data, but we significantly modified it to include the effects of current and anteceent soil water content, soil temperature, and vegetation greenness. We showed that long-term warming had little effect on annual Reco under ambient CO2, but stimulated it under elevated CO2 (32% across all years) when precipitation was high (e.g., 44% in 2009, a 'wet' year). Treatment-level differences in Reco can be partly attributed to the effects of antecedent soil temperature and vegetation greenness on the apparent temperature sensitivity of Reco and to the effects of antecedent and current SWC and vegetation activity (greenness modulated by VPD) on Reco base rates. Thus, this study indicates that the incorporation of both antecedent environmental conditions and aboveground vegetation activity are critical to predicting Reco at multiple timescales (subdaily to annual) and under a future climate of elevated CO2 and warming.

This paper was published in *Global Change Biology* in 2015, and we provided supplemental documents that included descriptions of our approach for gap-filling the environmental data, assessment of model performance, time-series of predicted Reco over 5 years, among other results.

Ecosystem Gross Primary Productivity (GPP) analysis

We extended and modified the Bayesian model that we applied to the Reco data to also analyze the temporal patterns and factors influencing ecosystem-level GPP. This study was motivated by the "fact" that determining whether the terrestrial biosphere will be a source or sink of carbon (C) under a future climate of elevated CO2 (eCO2) and warming requires accurate quantification of gross primary production (GPP), the largest flux of C in the global C cycle. Thus, to address this need, we evaluated six years (2007-2012) of flux-derived GPP data from the PHACE experiment. In particular, we developed a mixed effects model that we applied to the GPP data that extended a light response model to include the effects of environmental (soil water content, vegetation greenness, nitrogen) and meteorological variables (air temperature, vapor pressure deficit, photosynthetically active radiation) at current and past (antecedent) times. We found that stimulation of cumulative six-year GPP by warming (20%, P=0.06) and eCO2 (19%, P=0.14) was primarily driven by enhanced C uptake during spring (96%, P=0.003) and fall (115%, P=0.001), respectively. These enhancements were consistent across each year, suggesting mechanisms for extending the growing season. We also identified potentially important temporal lags between GPP and environmental drivers. For example, vapor pressure deficit from 1-3 days prior was the most significant predictor of temporal variability in GPP and for explaining treatment differences in GPP, suggesting that atmospheric drought plays an important role for predicting GPP under current and future climate conditions. This paper is under revision for *New Phytologist*.

Bayesian solution to isotope partitioning of soil respiration

Ogle and Pendall (2015) developed a Bayesian model to incorporate ^{13}C data from soil and soil respired CO_2, and the isotopic composition of root and microbial end members, to partition the respired CO_2 flux into its two main components. This paper was published in the *Journal of Geophysical Research: Biogeosciences*, and we included a detailed supplemental file that documents the model, and additional supplement file with the model code, which was implemented in OpenBUGS, a free software package for conducting Bayesian analyses. We are currently applying the approach to PHACE datasets involving carbon isotope fluxes (^{13}C), soil incubations, and soil respiration to evaluate the contribution of “old” versus “new” carbon sources to ecosystem C efflux. We have completed most of the coding for this analysis, and have compiled all data. We will finish the modeling and manuscript in summer 2016.

Hierarchical Bayesian solution to estimating trace gas fluxes

Ogle, Pendall, Ryan (former post-doc), and Dijkstra completed a modeling / statistical methods study that provides an improved approach for estimating trace gas (e.g., CO2, CH4) fluxes from non-steady state soil chambers. Non-steady state chambers are often employed to measure greenhouse gas fluxes. Gas concentrations (C) in the headspace are sampled at different times (t), and for each group of measurements, flux rates (f) are calculated from regressions of C versus t. While non-linear regressions are more accurate than linear regressions, a trade-off with precision can arise due to variability in the data leading to poor curve fits, and groups of data with too few observations or poor fits are often discarded. We solved these problems by fitting a non-steady state model of C versus t based on simple diffusion theory, embedded in a hierarchical Bayesian framework that accommodates the experimental design. We applied the modeling approach to data are from the PHACE study that manipulated atmospheric CO_2, temperature, soil moisture, and vegetation. CO_2 was collected from static chambers bi-weekly during five growing seasons, resulting in >12,000 samples and >3100 groups of samples and associated fluxes. Using these data, we compare f estimates from our hierarchical, non-steady state model to those obtained from non-hierarchical linear and non-steady state models. The f estimates from the hierarchical model and the non-hierarchical linear model fit the data well ($R^2 = 0.97$ and 0.98, respectively), but the linear model resulted in estimates that were ~10% lower than the hierarchical model. All three models produced similar estimates ($r \geq 0.93$), but the hierarchical model yielded notably more precise estimates. Overall, the hierarchical, non-steady state approach to estimating *f* is a significant improvement upon traditional non-hierarchical (independent groups) approaches. This paper is in review with *JGR-Biogeosciences*, and it includes supplemental materials with the Bayesian model code, with additional code that provides alternative ways of implementing the model / analysis (e.g., via R, paired with JAGS or OpenBUGS packages, or directly via OpenBUGS user interface).

7.3 DETECT Model: Dr. Kiona Ogle, Dr. Edmund Ryan, Dr. Elise Pendall

Development of the *DEconvolution of Temporally varying Ecosystem Carbon componenTs* (DETECT) model:

Kiona Ogle—formerly at Arizona State University (ASU; Jan 2011-June 2015), now at Northern Arizona University (NAU; Aug 2015-present)—supervised the development of the DETECT model for the DOE-TES PHACE project, which was primarily achieved by former post-doc, Edmund Ryan (now at Lancaster University in the U.K.). The DETECT modeling work is being continued by Kimberly Samuels-Crow, a post-doc in Ogle's lab, supported on Ogle's NAU faculty start-up. The DETECT model, and its associated code (in Matlab), is also serving as an important test example (case study) for the development of a new, fast, and cheap parallelization framework in Matlab (HPCMatlab) that ASU collaborators in the Advanced Computing Center (A2C2) are developing and testing.

DETECT is based on partial differential equations of soil CO2 transport and production, applied to a soil depth of 80 cm. We have improved the computational efficiency of DETECT and researched approaches to describing the source term and how to specify the matrix of diffusion coefficients used in the model. In particular, accurate estimation of the source term is critical as it represents the production of CO_2 at each of the soil layers for each time step. The improvements also include a representation of physical components of CO_2 production or loss in the source term, for example, carbonate dissolution. At the heart of the model, the partial differential equation simulates the transport of CO_2 between different layers and time through the diffusion of the gaseous components of CO_2. An Euler approach is used to obtain numerical solutions to the PDE's underlying the DETECT model.

An essential aspect of the DETECT model is the driving data, in particular soil water content, soil temperature and water potential. These are required for each of the 20 soil layers, yet there is only information on these three quantities at a handful of soil layers. An undergraduate student (Ian Blackburn) and a former graduate student (Heather Kropp) in the Ogle lab parameterized the 2-dimensional HYDRUS soil water model for the PHACE site. This dynamic soil water model is based on the Richards equation for soil water transport. We used the HYDRUS model to produce site-specific soil moisture and temperature data at 1-cm increments, down to 100 cm, which we subsequently used to drive the DETECT model.

We are working on two primary projects involving the DETECT model, which we will refer to as DETECT Part 1 and Part 2. The simulations associated with **Part 1** are completed, and we are finishing the manuscript. Part 1 is motivated by the observation that soil respiration (or efflux) of carbon (C) from the Earth's surface (Rsoil) is a major flux in the global carbon cycle, and is predicted to increase under a future climate of elevated atmospheric CO2 and warming. Methods to measure and model Rsoil, or partition it into different components, often rely on the assumption that soil CO2 concentrations and/or fluxes are in steady state; this means that Rsoil (soil-atmosphere CO2 flux rate) is equal to the rate by which CO2 is produced within soil profile by microbial decomposition of soil organic matter and the respiration of roots. Recent research disputes the validity of this assumption.

The aim of this work is to evaluate under what environmental conditions steady-state is likely. We achieved this by numerically solving DETECT's non-homogeneous partial differential equation (PDE) that describes the non-steady-state (NSS) production and transport of soil CO2 to a depth of 1 meter in 1cm increments and during April-September of 2008 at six-hourly time-steps. Production of soil CO2 was simulated for every depth and time and based on microbial decomposition and root respiration of CO2, which were driven by current and antecedent environment data (e.g. soil water content and soil temperature data) which also varied by time and depth. We analytically solved the steady-state (SS) version of the PDE as well. Both PDE models were run under three different scenarios to determine their effects on predicted Rsoil: (1) varying the soil texture; (2) shifting the timing or frequency of precipitation; (3) with and without antecedent driving variables. For a coarse textured soil (60% sand), the daily Rsoil from the SS model roughly matched (≤5% difference) that of the NSS model, during the majority of the growing season (March – September). However, if the soil was predominantly finely textured (60% silt or 60% clay), then growing season Rsoil was larger than Rsoil from a 60% sand soil by 25-150% depending upon whether the SS or NSS model was used or whether soil CO2 production incorporated past conditions. Furthermore, Rsoil was ~30% larger under the assumption of NSS (versus SS) for the 60% clay scenario. Predicted Rsoil was similar for both NSS and SS models, regardless of antecedent environmental conditions, precipitation timing and frequency. A further novel aspect of this research was the use of high performance computing and advanced parallelization, which significantly reduced the running time of the NSS model from 13.5 minutes to 20-40 seconds.

The second study involving DETECT (Part 2) is underway. All DETECT simulations have been completed, and we are in the process of analyzing the DETECT output. A major goal of this study is to evaluate and quantify the temporal lags and strengths of correlation between Rsoil, CO2 production (within the soil), and key environmental drivers (i.e., soil temperature and water content at different depths). We are motivated by the observation that most empirical analysis of observed Rsoil and/or isotope-based studied focusing on partitioning of Rsoil, implicitly assume no temporal lags between Rsoil and production or

Rsoil and its environmental drivers. We conducted a suite of simulations with detect to evaluate the appropriateness of such assumptions under different soil textures, different depth-distributions of soil microbes and roots, and different assumptions about antecedent environmental effects. We used wavelet coherence analysis and correlation analyses to estimate and identify lags and correlations between Rsoil, production, and soil temperature and water. We found that temporal lags between these quantities are prevalent, especially in fine-textured soil, following rain events, and during certain times of year. The strongest lags occur at sub-daily time scales and likely reflect lags due to diffusion of CO2 within the soil profile, which can be slowed in fine-textured soils, soil characterized by high CO2 production in deeper layers, and during times following rain events that reduce the amount of air-filled pore space. These results have implications for how we analyze and interpret measurements of Rsoil, Reco, and their associated C isotopes.

7.3. FACE Model Inter-comparison Synthesis:

The FACE Model-Data Synthesis project has been expanded to include four elevated CO2 experiments—the Wyoming prairie heating and CO2 experiment (PHACE), Rhinelander FACE, Duke FACE, and the Kennedy Space Center Open Top Chamber experiment—in addition to the Duke and Oak Ridge FACE experiments previously analysed. The purpose of the project was to broaden the range of climate and ecosystem types allowing further questions to be tested and more general conclusions to be drawn that was not possible with two sites with similar climatic regimes.

Twelve terrestrial ecosystem/carbon cycle models were used to simulate the six experiments. Models were applied to the sites following a common protocol which specified meteorological data, CO2 data, common parameterisations of soil characteristics, plant traits, and site land use history. The models we used were seven global land surface models: CABLE, CLM4.0, CLM4.5, ISAM, JULES, O-CN, and ORCHIDEE; two global dynamic vegetation models: LPJ-GUESS and SDGVM; and three ecosystem models DAYCENT, GDAY, and TECO (Clark et al., 2011; De Kauwe et al., 2014; Oleson et al., 2013; Walker et al., 2014; Zaehle et al., 2014). Quality controlled simulations were finalised in September 2015 and analyses and manuscript drafting is under way. We expect these manuscripts to be ready for submission through 2016 and early 2017.

Specific objectives of the FACE-MDS project are to synthesize response datasets and make available on the CDIAC website, along with processed meteorological data. Site meteorological data will be made available in March 2016 and response data in late 2016 (http://cdiac.ornl.gov/face/).

Science objectives of the FACE-MDS (manuscripts in preparation):

- Does elevated CO2 mitigate drought effects in diverse ecosystems of the US?

- Effect of temperature variation on CO_2 responses at the PHACE experiment.
- Decade long carbon sequestration in forest live biomass in response to CO_2 enrichment.
- Analyse the priming effect under CO_2 enrichment through implementation of a common hypothesis in multiple models.
- Identify source of uncertainties in modeled terrestrial ecosystem carbon storage capacity and its response to elevated CO_2: a traceability analysis.

The FACE-MDS targets the Terrestrial Ecosystem Science goal detailed in the 'Climate and Environmental Science Division Strategic Plan' (2012) to: "Analyze long-term ecosystem observational records to inform and evaluate models." A primary rationale for DOE's investment in the FACE program was to provide an assessment of the importance of the CO_2 fertilization effect in the global carbon cycle. The long-term and large-scale nature of the questions requires the use of models, but the models should be informed by relevant data from experiments.

7.4. Database development and publication

Major progress on the database was facilitated by the hard work of several team members. Project director Pendall applied the principles of a semester-long Ecoinformatics course to developing the relational database structure for the PHACE experiment. A postdoc and a graduate student on the project also received training in database management and utilization. Data Manager Samantha Ewers has had primary responsibility for collecting all data related to the project, validating it and entering it to the PHACE Ecosystem database, which was converted from Microsoft Access to a SQL server. We are still working with UW Information Technology to provide access to the SQL server outside the UW firewall, but in the meantime we are publishing datasets along with manuscripts, and sharing data freely with an extensive network of collaborators. Our goal is to make all data publicly available in the coming year, pending publication of key manuscripts still in progress.