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MIDWESTERN REGIONAL CENTER OF THE DOE NATIONAL INSTITUTE FOR CLIMATIC CHANGE RESEARCH

Final Technical Report for the Period December 1, 2005 – November 30, 2013

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***Executive Summary*:**

The goal of NICCR (National Institute for Climatic Change Research) was to mobilize university researchers, from all regions of the country, in support of the climatic change research objectives of DOE/BER. The NICCR Midwestern Regional Center (MRC) supported work in the following states: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio. The MRC of NICCR was able to support nearly $8 million in climatic change research, including $6,671,303 for twenty projects solicited and selected by the MRC over five requests for proposals (RFPs) and $1,051,666 for the final year of ten projects from the discontinued DOE NIGEC (National Institute for Global Environmental Change) program. The projects selected and funded by the MRC resulted in 135 peer-reviewed publications and supported the training of 25 PhD students and 23 Masters students. Another 36 publications were generated by the final year of continuing NIGEC projects supported by the MRC.

The projects funded by the MRC used a variety of approaches to answer questions relevant to the DOE's climate change research program. These included experiments that manipulated temperature, moisture and other global change factors; studies that sought to understand how the distribution of species and ecosystems might change under future climates; studies that used measurements and modeling to examine current ecosystem fluxes of energy and mass and those that would exist under future conditions; and studies that synthesized existing data sets to improve our understanding of the effects of climatic change on terrestrial ecosystems. In all of these efforts, the MRC specifically sought to identify and quantify responses of terrestrial ecosystems that were not well understood or not well modeled by current efforts. The MRC also sought to better understand and model important feedbacks between terrestrial ecosystems, atmospheric chemistry, and regional and global climate systems. Where possible, the MRC supported projects that leveraged multiple funding sources, including NICCR, to achieve results beyond those that would result from NICCR support alone. In general, these efforts involved MRC support of new measurements or manipulations within an existing experimental framework.

Highlights of the extensive findings of the funded projects include a new, fine resolution crop model (i.e. SiBcrop) developed by Denning (RFP01) and coupled with RAMS (a regional atmospheric model), enabling improved prediction of carbon and other land-atmosphere exchanges in croplands. Reich (RFP01 and 04) found that when soil resources are at limiting supply, the CO_2 fertilization effect on biomass production is reduced, or even eliminated, casting doubt on the main models used in the IPCC assessment, which continue to assume large increases in plant biomass production due to rising atmospheric CO_2 concentrations. In northern forests undergoing succession from pioneer species to late-successional species, long-term resilience of C storage to disturbance was found to be dependent upon canopy structural reorganizations that enhance carbon uptake (Curtis and collaborators, RFP01 and 04). Takle (RFP01) developed modeling tools for merging global and regional climate model output into ecosystem models such as the CENTURY model for predicting future soil C. Changes in the timing of rainfall events (larger events with longer inter-rainfall droughts), without a change in total precipitation amount, were found to alter soil moisture dynamics, causing significant reductions in both grassland plant productivity and soil respiration (Blair and Knapp, RFP02 and 05). Ecosystem carbon cycle models were failing to explain interannual variability in CO_2 fluxes in the upper Midwest, and Desai and MacKay (RFP02) identified the causal role of a lack of

model mechanisms for wetland biogeochemistry and hydrology for this shortcoming and intiated work on model improvements to address the issue. Long (RFP02) found that elevated [CO_2] will ameliorate drought stress effects on both C3 and C4 components of Midwest agroecosystem less than previously assumed. When applied in combination, to crops, the benefits of higher CO_2 offset the negative impact of higher temperatures (Bernacchi, RFP04). Kucharik and Lenters (RFP03) incorporated groundwater (depth-to-water) into the Agro-IBIS model, improving the accuracy of its predictions of carbon and water cycling in Midwestern croplands and wetlands. Twine and Leakey (RPF03) found that 20 - 25% of recent crop yield trends can be explained by changing climate, and suggest that over the past several decades, climate changes have favored increased crop productivity in most agroecosystems of the central U.S. with the exception of winter wheat. Constraints on the amount of C allocated to root/mycorrhizal system respiration in experimentally warmed forest soils were found by Burton (RFP03), suggesting that many current models will overestimate belowground C allocation for root and mycorrhzial respiration for warming scenarios, which could lead to underestimates of future net primary productivity. Root-soil interactions strongly regulated the response of soil organic carbon decomposition to warming, with soil warming substantially intensifying the rhizosphere priming effect on SOM decomposition (Cheng, RFP04). In a one-year project, Campbell (RFP05) made substantial progress toward developing a method to partition the net ecosystem exchange (NEE) into gross primary production (GPP) and respiration fluxes during recent Midwest carbon-climate anomalies using simulated and observed airborne measurements of carbonyl sulfide (COS) and CO_2.

The broad variety of projects the MRC has supported gave us a unique opportunity to greatly improve our ability to predict the future health, composition and function of important agricultural and natural terrestrial ecosystems within the Midwestern Region. Several of these projects have been able to continue beyond their initial MRC funding and continue to contribute to our scientific understanding of and ability to model the responses of terrestrial wetlands, forests, rangeland and crop systems to climatic change.

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Final Technical Report: Midwestern Regional Center of the DOE National Institute for Climatic Change Research

This report describes the activities conducted by the DOE NICCR Midwestern Regional Center (MRC). The goal of NICCR (National Institute for Climatic Change Research) was to mobilize university researchers, from all regions of the country, in support of the climatic change research objectives of DOE/BER. The MRC supported work in the following states: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio.

After describing the administrative process utilized by the MRC to solicit, select, fund and administer University research within the region, this report then provides brief summaries of the of the funded projects, highlighting their key findings.

NICCR MRC Adminstrative Procedures

Solicitation of Proposals. The NICCR conducted five requests for proposals (RFPs) during its existence. The announcement and links to each RFP were placed on the national NICCR website (http://niccr.nau.edu) and the websites for the regional centers (http://niccr.mtu.edu for the Midwestern Regional Center). For all RFPs, potential applicants were solicited nationally through announcements on webpages and list servers for ecological, environmental, biogeochemical and atmospheric scientists. These included the AGU Biogeosciences webpage, the Ecophys webpage, the ESA list server Ecolog, the AmeriFlux list server, the Isogeochemistry list server, the S-7 (forest, range and wildland soils) list server, and two ASHS list servers. National announcements were also made by regional center directors at the annual meetings of groups such as the Ecological Society of America, the Soil Science Society of America, and the American Geophysical Union. Within the Midwestern Region, we also directly solicited proposals by sending the announcement to the Vice Presidents of Research at universities within the region, who then passed the announcement along to appropriate Deans and Directors.

Table 1. Announcement, submission and start dates for the first five NICCR RFPs.

	Announcement date	Preproposal due date	Full proposal due date	Anticipated start date
RFP-01	1 Dec 2005	18 Jan 2006	14 Mar 2006	1 Sep 2006
RFP-02	7 Aug 2006	19 Sep 2006	5 Dec 2006	1 Jul 2007
RFP-03	3 Apr 2007	15 May 2007	21 Aug 2007	1 Apr 2008
RFP-04	28 Feb 2008	16 May 2008	15 Aug 2008	1 Apr 2009
RFP-05	1 Mar 2009	15 May 2009	14 Aug 2009	1 Apr 2010

Preproposals. One page preproposals were required by each RFP. Response to the RFPs was strong, with the Midwestern Regional Center (MRC) receiving 81 preproposals in response to RFP-01, 43 for RFP-02, 39 for RFP-03 and 30 for RFP-04, and 26 for RFP-05. Preproposals to the MRC received from 7 to 15 reviews. Preproposal reviews were provided by the MRC Director, three ad-hoc reviewers selected by the MRC Director, the Director and/or Assistant Director from each of the other four NICCR Centers, NICCR's National Program Manager (Dr. Jeffrey Amthor) and two to four nationwide ad-hoc reviewers, who reviewed preproposals from all five NICCR Centers. Reviewers provided a single numerical score from 0-10 for each preproposal. Each score was based on scientific merit (50%) and adherence to the terms of the

RFP (50%). Each reviewer provided a score for all proposals received by the MRC, unless they had a conflict of interest with the PI(s) or institution of the preproposal.

The MRC Director examined the preproposal scores for the Midwestern Region and developed a preliminary list of preproposals for which full proposals would be requested. The mean score was used to develop an initial list, which was then modified based on the median score, to ensure that a preproposal viewed favorably by most was not excluded due to one or two excessively low scores. This list was discussed with the National Program Manager and the Directors of the four other NICCR Centers during a conference call held approximately two weeks after the preproposal deadline. During that call, the list of preproposals for which full proposals would be requested was finalized.

Full Proposals and Panel Review. The MRC solicited 24 full proposals for RFP-01, 17 for RFP-02, 15 for RFP-03, 15 for RFP-04, and 13 for RFP-05. Proposals received from 5 to 8 reviews, provided by three to five panel members and one to three ad-hoc reviewers with expertise on the subject matter of the proposal. Reviewers were instructed to provide comments on the following five areas: 1) scientific merit of the proposal with respect to the focus areas specified in the RFP; 2) appropriateness of the proposed methods or approach; 3) competency of the applicant's personnel and adequacy of proposed resources; 4) reasonableness and appropriateness of the proposed budget; and 5) performance in previously funded NICCR or NIGEC research related to the proposal (if applicable). Based on the proposals strengths and weaknesses in these five categories, each reviewer then provided a numerical summary rating from 0 to 10, based on the following scale: Excellent [9-10], Very good [7-8], Good [5-6], and Poor/Fair [0-4].

For each RFP, a panel meeting, with 7 to 9 panelists, the MRC Director, and MRC Manager (Jill Fisher) was held approximately eight weeks after the proposal due date to discuss and prioritize the proposals. Several days prior to the meeting, panelists were provided all written reviews and scores for the proposals assigned to them. After discussing the strengths and weaknesses of each proposal, a consensus rating was determined (Excellent, Very Good, Good, Fair, or Poor) and a panel summary written. As a final step, the panel ranked the proposals based on funding priority (fund, possibly fund, do not fund). In some cases, the panel also recommended funding only those portions of a study that were highly relevant to NICCR's mission. Within the "fund" category, proposals were ordered based on the panel's consensus regarding the relative strength of the proposals within that group. The MRC Director organized these meetings and participated in synthesizing overall results, but did not lead any proposal discussions or influence the panel's recommendations.

Funding Decisions. Approximately two weeks after the MRC panel meeting, final funding decisions were made at the national NICCR Board of Directors Meeting (or teleconference for RFPs 04 and 05), attended by National Program Manager Amthor and the Directors and Assistant Directors of each NICCR Center. The MRC Director presented the MRC funding recommendations, which were discussed by the group. Final decisions were based on the MRC panel recommendations, availability of funds, and a desire to achieve balance among NICCR's four research foci both within and among regions. For RFP-02, RFP-03, RFP-04 and RFP-05, proposals from the MRC host institution (Michigan Technological University) were under consideration. In addition, during RFP-05 one proposal under consideration listed the MRC Director as a collaborator. To avoid conflict of interest, reviews for these proposals, provided by members of the MRC panel or solicited by National NICCR Program Manager Amthor, were sent directly to Dr. Amthor, who made the funding decision. Four proposals were funded under RFP-01, with a total three-year value of $1,775,171. One of these was a three-university collaborative proposal. Four proposals were funded under RFP-02, with a total three-year value of $1,639,040. Three of these were two-university collaborative proposals. Four proposals were funded under RFP-03, with a total three-year value of $1,651,442. Two of these projects were two-university collaborations and one was for research by the host institution. Four proposals were funded under RFP-04, with a total two-year value of $1,161,070. One of these was a three-university collaborative proposal, which also was a continuation of an RFP-01 project, but with one of the three universities changing. Four proposals were funded under RFP-05, with a total one-year value of $444,501. Two of the RFP-05 projects were one-year renewals of existing subawards, including a two-university collaborative, and two were entirely new one-year projects. In addition, the MRC allowed portions of its RFP-03 and RFP-04 allocations from DOE-BER ($37,933 and $28,268) to be sent to the Western Regional Center, to help fund a portion of a cross-regional project. During the first year of the NICCR program, the MRC also supported one year of research for ten pre-existing projects from the former NIGEC program, with a total value of $1,051,666.

All reviews, the panel summary, and the consensus rating were provided to the PI of each proposal after budget negotiations with successful PIs (see below) and announcement of the final funding decisions.

Establishing Subcontracts. Budgets were re-negotiated, if necessary, with the PIs of the successful proposals, after which revised budgets were submitted to the MRC by their institutions. The MRC then requested a supplement to Michigan Tech's existing cooperative agreement with DOE (DE-FC02-06ER64158) in the amount needed to fund the first year of new proposals and the next increment of continuing proposals from prior RFPs. During the first year of the cooperative agreement, supplemental funds were also requested for a final year of research for ten projects initially funded under the NIGEC program. After these supplemental requests were granted by DOE, subcontracts were established with new projects and second (or third) year increments were provided to continuing projects.

Monitoring Progress. Each funded project submitted an annual progress report to the MRC 30 days prior to a project's annual continuation funding date. Final Reports are due 45 days after a project's end date. Collaborative projects are allowed to submit a single report covering all institutions involved. Reports focused on major activities and research highlights and contained: 1) an abstract summarizing the project and written in a style that allows project results and their significance to be understood by an educated audience of non-specialists; 2) research activities; 3) research highlights, including figures and tables that clearly illustrate major results; 4) research products (models, websites, etc.); 5) publications; and 6) student degrees supported. Reports were reviewed by the MRC Director; funding of the project's remaining years is dependent on adequate, timely progress in addressing the objectives outlined in the project's proposal. The abstracts and publication lists from the projects were posted on the MRC website, as well as links to any websites for the individual projects. The publication lists are also included in the MRC's progress report to the DOE.

Description of Projects Funded by the NICCR MRC

Value to DOE. The MRC selected proposals that addressed one of four research foci:

Focus 1 projects addressed potential effects of climatic change on terrestrial ecosystems, determining the theoretical and/or empirical basis of whether, and how, changes in temperature and/or changes in precipitation might affect the structure and functioning of important U.S. terrestrial ecosystems.

Focus 2 projects improved the scientific basis for detecting or projecting changes in the geographic boundaries of U.S. terrestrial ecosystems (or biomes), and the populations of their dominant organisms, in response to potential climatic changes.

Focus 3 projects addressed the measurement and analysis of contemporary exchanges of mass and energy between the atmosphere and regionally important terrestrial ecosystems or landscapes, and the use of those measurements and analyses to evaluate mechanisms that might be included in climate and carbon cycle models.

Focus 4 projects will carried out synthesis activities related to effects of climatic variability and change on U.S. terrestrial ecosystems, or feedbacks from terrestrial ecosystems to climatic change, principally with a regional focus.

The projects funded by the MRC (Table 2) used a variety of approaches to answer questions relevant to the DOE's climate change research program. These included experiments that manipulated temperature, moisture and other global change factors; studies that sought to understand how the distribution of species and ecosystems might change under future climates; studies that used measurements and modeling to examine current ecosystem fluxes of energy and mass and those that would exist under future conditions; and studies that synthesized existing data sets to improve our understanding of the effects of climatic change on terrestrial ecosystems. In all of these efforts, we specifically sought to identify and quantify responses of terrestrial ecosystems that are not well understood or not well modeled by current efforts. We also sought to better understand and model important feedbacks between terrestrial ecosystems, atmospheric chemistry, and regional and global climate systems. Where possible, the MRC supported projects that leveraged multiple funding sources, including NICCR, to achieve results beyond those that would result from NICCR support alone. In general, these efforts involved MRC support of new measurements or manipulations within an existing experimental framework. For RFP-05, one-year synthetic projects combining aspects of experimental manipulations, simulation modeling, and observational studies were strongly encouraged.

The broad variety of projects the MRC has supported gives us a unique opportunity to greatly improve our ability to predict the future health, composition and function of important agricultural and natural terrestrial ecosystems within the Midwestern Region. To further achieve our goals, we encouraged the PIs of our projects to communicate their needs and results with each other and the scientific community in general in order to bring together results of modeling, synthesis and experimental projects. We wanted modelers to have access to the most recent results of manipulative experiments and synthesis projects. We wanted experimentalists to target their efforts at generating data for important processes that are poorly handled or lacking in current models, and we want those modeling exchanges of energy and mass to have comprehensive current flux data for verifying the accuracy of their models and improvements. A focus on collaboration among projects helped foster synthesis of existing data from independent experiments, both to develop research hypotheses and to verify the applicability of regional results to larger scales and additional ecosystems.

Table 2. Projects funded by the Midwest Regional Center of NICCR under RFP01 through RFP05.

PI	Institution	Project title	Focus	Amount	Duration
Peter Reich	University of Minnesota	Interactive effects of carbon dioxide, water, and nitrogen on grassland ecosystem processes	1	$375,000	RFP01, 3 yrs
Peter Curtis	Ohio State University	Disturbance, succession and forest carbon dynamics: an ecosystem-scale experiment at the UMBS AmeriFlux site	3	$149,166	RFP01, 3 yrs
Christoph Vogel	University of Michigan	Disturbance, succession and forest carbon dynamics: an ecosystem-scale experiment at the UMBS AmeriFlux site	3	$359,347	RFP01, 3 yrs
Hans Schmid	Indiana University	Disturbance, succession and forest carbon dynamics: an ecosystem-scale experiment at the UMBS AmeriFlux site	3	$141,216	RFP01, 3 yrs
Scott Denning	Colorado State University	Land-Atmosphere Exchanges of Carbon, Water, and Energy Across the Midcontinental Region of North America: Processes, Scaling, and Evaluation	4	$375,457	RFP01, 3 yrs
Eugene Takle	Iowa State University	Evaluating effects of climate changes on Midwest agroecosystems using a climate-crop coupled model	4	$374,985	RFP01, 3 yrs
John Blair	Kansas State University	Collaborative research: Assessing long-term plant and soil responses to altered rainfall timing and elevated temperature in grassland ecosystems	1	$365,922	RFP02, 3 yrs
Alan Knapp	Colorado State University	Collaborative research: Assessing long-term plant and soil responses to altered rainfall timing and elevated temperature in grassland ecosystems	1	$136,630	RFP02, 3 yrs
Rod Chimner	Michigan Tech University	Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resilience to climate change	1	$268,148	RFP02, 3 yrs
Merritt Turetsky	Michigan State University	Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resilience to climate change	1	$123,988	RFP02, 2 yrs
Ankur Desai	University of Wisconsin	Improving prediction of climate change impacts on wetland-rich landscapes: testing model mechanisms with flux-data assimilation at multiple sites	3	$280,918	RFP02, 3 yrs
Scott Mackay	SUNY Buffalo	Improving prediction of climate change impacts on wetland-rich landscapes: testing model mechanisms with flux-data assimilation at multiple sites	3	$93,776	RFP02, 3 yrs
Stephen Long	University of Illinois	How will productivity, evapotranspiration & insect herbivory of the Midwest agroecosystem respond to drought & elevated CO2 anticipated for 2050?	1	$369,658	RFP03, 3 yrs
Chris Kucharik	University of Wisconsin	Impacts of historical and future changes in climate and atmospheric CO_2 on terrestrial ecosystem structure and functioning in the Midwestern US	3	$229,197	RFP03, 3 yrs
John Lenters	University of Nebraska, Lincoln	Impacts of historical and future changes in climate and atmospheric CO_2 on terrestrial ecosystem structure and functioning in the Midwestern US	3	$132,979	RFP03, 3 yrs

Yiqi Luo	University of Oklahoma	Experimental and modeling study of interactive effects of warming and altered precipitation on function and structure of a tallgrass prairie in the Great Plains	1	$388,142	RFP03, 3 yrs
Tracy Twine	University of Minnesota	Agroecosystems: Effects of changes in climate, carbon dioxide, and ozone over the central United States	4	$194,408	RFP03, 3 yrs
Andrew Leakey	University of Illinois	Agroecosystems: Effects of changes in climate, carbon dioxide, and ozone over the central United States	4	$166,309	RFP03, 3 yrs
Andrew Burton	Michigan Tech University	Short and long-term temperature acclimation of roots systems in woody plants and the moderation of warming-induced enhancement of soil CO2 efflux	1	$540,387	RFP03, 4 yrs
Peter Curtis	Ohio State	Collaborative research: Disturbance, succession and forest carbon dynamics: a large-scale manipulation at the University of Michigan Biological Station	3	$115,267	RFP04, 2 yrs
Christoph Vogel	University of Michigan	Collaborative research: Disturbance, succession and forest carbon dynamics: a large-scale manipulation at the University of Michigan Biological Station	3	$249,993	RFP04, 2 yrs
Chris Gough	Virginia Commonwealth University	Collaborative research: Disturbance, succession and forest carbon dynamics: a large-scale manipulation at the University of Michigan Biological Station	3	$59,637	RFP04, 2 yrs
Peter Reich	University of Minnesota	Interactions among water CO_2 and N in a perrenial grassland ecosystem	1	$245,000	RFP04, 2 yrs
Carl Bernacchi	University of Illinois	The Interactive effects of elevated temperature and CO_2 applied under field conditions on a soybean ecosystem	1	$245,000	RFP04, 2 yrs
Weixin Cheng	University of California, Santa Cruz	Partitioning responses of rhizosphere respiration and soil organic carbon decomposition to warming and altered precipitation in a grassland ecosystem	1	$246,273	RFP04, 2 yrs
John Blair	Kansas State University	Collaborative research: Assessing long-term plant and soil responses to altered rainfall timing and elevated temperature in grassland ecosystems	1	$80,773	RFP05, 1 yr
Alan Knapp	Colorado State University	Collaborative research: Assessing long-term plant and soil responses to altered rainfall timing and elevated temperature in grassland ecosystems	1	$21,227	RFP05, 1 yr
J. Elliott Campbell	University of California, Merced	Quantifying carbon cycle partitioning during climate anomalies using atmospheric carbonyl sulfide (COS)	3	$112,500	RFP05, 1 yr
Sarah Hobbie	University of Minnesota	Experimental warming effects on soil organic matter dynamics at the temperate-boreal forest ecotone	1	$117,500	RFP05, 1 yr
Rod Chimner	Michigan Tech University	Predicting how CH4 formation, transport pathways and flux rates in peatlands will respond to climate change	1	$112,500	RFP05, 1 yr
Total				$6,671,303	

Table 3. DOE NIGEC projects Funded for their Final Year by the NICCR Midwestern Regional Center.

PI	Institution	Project title	Amount	Duration
Tim Arkebauer	University of Nebraska, Lincoln	Controls on Soil Surface CO2, N2O and CH4 Fluxes, Ecosystem Respiration and Global Warming Potentials in Great Plains Agricultural Ecosystems	$99,741	1 yr
Teri Balser	University of Wisconsin	Evaluating changes in soil carbon cycling in reed canary grass invaded soils subject to elevated atmospheric CO_2 and increased soil nitrogen	$89,875	1 yr
John Blair	Kansas State University	Effects of Altered Rainfall Timing and Warming on Soil and Plant Responses in a Grassland Ecosystem	$135,837	1 yr
Paul Bolstad	University of Minnesota	Are North Temperate Wetlands A Persistent Net Source of Atmospheric CO_2? Component and Whole-System CO2 Fluxes in a Landscape Mosaic	$98,997	1 yr
William Easterling	Pennsylvania State University	Climate Impact Modeling and Analysis Project (CIMAP)	$78,000	1 yr
Ross Fitzhugh	University of Illinois	Carbon and nitrogen dynamics and retention in an agricultural ecosystem under elevated atmospheric carbon dioxide and ozone	$104,501	1 yr
Jay Ham	Kansas State University	Net Ecosystem Carbon and Water Vapor Exchange of Tallgrass Prairie: Component Fluxes and Spatial Heterogeneity	$63,800	1 yr
Chris Kucharik	University of Wisconsin	Improving and Evaluating Dynamic Models of Natural and Managed Ecosystems over the Central and Southern U.S. Using AmeriFlux and MODIS Data	$112,915	1 yr
Terry Mader	University of Nebraska, Lincoln	Evaluation of ecosystem models for beef cattle production	$98,000	1 yr
Hans Schmid	Indiana University	Forest-Atmosphere Exchange of CO_2 over a Mixed Hardwood Ecosystem in the Midwest	$170,000	1 yr
Total			$1,051,666	

Key Accomplishments of Funded Projects. Highlights for each NICCR MRC funded project are provided below. The final reports submitted to the MRC for each project, including figures and tables, can be found in the Appendix.

"Interactive effects of carbon dioxide, water, and nitrogen on grassland ecosystem processes" (RFP01) and ***"Interactions among water, CO_2 and N in a perrenial grassland ecosystem"*** (RFP04). PI Peter Reich, University of Minnesota. Total funding $620,000 for five years.

This project focused on how inputs of water to terrestrial ecosystems interact with atmospheric CO_2 and soil nitrogen (N) supply to affect ecosystem structure and function. The experiment used free-air CO_2 enrichment, soil N additions, and precipitation removal (using portable rain-out shelters) to expose open-grown established experimental grassland plots to all combinations of two levels of each factor. Using NICCR funding they built 24 portable rain-out exclosures, each 2 x 2 m in area, which removed approximately 40-45% of the rainfall. Results from 2007-2011 demonstrated a number of responses to water, nitrogen, and CO_2. Light-saturated net photosynthesis (*A*) was moderately stimulated by *e*CO_2, by a similar extent for both the $AmbH_2O$ and $LowH_2O$ treatments. Stomatal conductance was reduced by *e*CO_2 across treatments as expected (-25%, CO2 p = 0.0754), however to a lesser extent under $LowH_2O$ and elevated N (compared to other treatment combinations). This response was consistent across species. Results showed that *e*CO2 induced stimulation of net photosynthesis increases as soil conditions become drier. Over the 2007-2011 period, there was a three-way interaction between CO_2, N and water treatments (P=0.0034) on aboveground biomass; such that when both water and N supply were at their lower levels, the response to elevated CO_2 disappeared; whereas at treatments where one or both of water and N were at their higher respective levels, there was a strong positive CO_2 effect. This strongly suggests that when soil resources are at limiting supply, the CO_2 fertilization effect on biomass production will be reduced, or even eliminated, casting doubt on the main models using the IPCC assessment which continue to assume (i.e. built into model algorithms) large increases in biomass production due to rising atmospheric CO_2 concentrations. Additionally, on average from 2007-2011, the root fraction (total root biomass as fraction of total plant biomass) was increased by the "low-water" treatment at low levels of both CO_2 and N, consistent with the notion of increased root allocation towards a limiting resource. However this response was reversed at enriched levels of N and CO_2 .

Seedlings of *Pinus strobus*, *Quercus macrocarpa* and *Q. ellipsoidalis* seeds were planted each spring to allow study of treatment effects on seedling survival and recruitment in the herbaceous communities. By the end of 2011, oaks (pooling bur and red) planted in 2007 and 2008 were more numerous and larger (diameter and height) in *e*CO_2 than ambient CO_2. CO_2 effects on those planted in 2010 and 2011 were minimal. For those planted in 2007 and 2008 (both bur and red), individuals surviving to end of 2011 were fewer in low water treatment but larger. Water treatments did not significantly influence numbers or size of oaks surviving to end of 2011 for those planted in 2010 or 2011. For N, the main impact for both species was fewer survived to the end of 2011 under enriched than ambient N, and those that did were smaller. For both water and N, it is possible that higher soil resources increased herbaceous production and competitively suppressed oak seedling growth.

Project results can and data can be found on both web page for the main BioCON experiment: http://www.biocon.umn.edu/index.html, and that for the NICCR funded Water Experiment: http://www.biocon.umn.edu/water_experiment.html. This project had supported five peer reviewed papers by the end of the funding period, with others expected as the data is analyzed and the BioCON experiment continues under other funding sources.

"Disturbance, succession and forest carbon dynamics: an ecosystem-scale experiment at the UMBS AmeriFlux site" (RFP01) and ***"Collaborative research: Disturbance, succession and forest carbon dynamics: a large-scale manipulation at the University of Michigan Biological Station"*** (RFP04). PIs: Peter Curtis, Ohio State University, Christoph Vogel, University of Michigan, Hans Schmid Indiana University , and Christopher Gough, Virginia Commonwealth University. Total funding $1,074,626 for five years.

This project sought to of uncover mechanisms behind shifts in carbon (C) cycling in response to disturbance, ecological succession, and ongoing climate change across the Upper Great Lakes Region. In 2008, they implemented the Forest Accelerated Succession Experiment (FASET) by stem girdling all aspen and birch within 39 ha in northern lower Michigan. Ecological, meteorological, and remote sensing measurements were used to quantify effects of climate, species composition, and canopy structure on the forest C cycle. There was a modest decrease in net ecosystem CO_2 exchange in the treatment area two years following disturbance, and although this treatment response was subtle, there was a cascade of biogeochemical changes that promoted functional resilience in the C cycle. There was near-complete retention of actively-cycling soil nitrogen and rapid replacement of senescing species' leaf area as soil N availability increased and was reallocated to new leaf area of later-successional trees. Long-term resilience of C storage to disturbance was found to be dependent upon canopy structural reorganizations that enhance carbon uptake. The resulting improved understanding of how forests work is enhancing science-based products, including models, that will inform land managers and policy makers how to manage forests in the backdrop of local and global environmental change.

This project posted NEE, ancillary meteorological data and comprehensive biological data from our tower cluster site (the UMBS AmeriFlux control site and the FASET disturbance site) to the Fluxnet data site at CDIAC. The project web site, listing many meta-data and biometric data is at: http://www.biosci.ohio-state.edu/~pcurtis/UMBS~Flux/index.htm. The project also encouraged numerous synergist activities with other investigators and the funding of new proposals to further a mechanistic basis for changes in C fluxes during forest succession. This project resulted in 20 peer review publications and supported the research of six PhD students and five MS students.

"Land-Atmosphere Exchanges of Carbon, Water, and Energy Across the Midcontinental Region of North America: Processes, Scaling, and Evaluation" (RFP01). PI Scott Denning, Colorado State University. Total funding $375,457 for three years.

This project used a coupled land-atmosphere modeling system (SiBcrop-RAMS) to analyze the regional scale carbon and other exchanges across the croplands in continental North America, subject to interannual variability of weather, management, and existing and expected changes in climate across the continent. Development of a new, fine resolution crop model (i.e. SiBcrop) and coupling it with RAMS (a regional atmospheric model developed at Colorado State University), was one of the major achievements of this project. Originally the land surface model named Simple Biosphere (SiB) model, did not have a good representation of the dynamic events and growth stages associated with the managed cropland ecosystems. This project incorporated a crop specific phenology and physiology scheme within SiB and developed SiBcrop, to further improve prediction of carbon and other land-atmosphere exchanges in croplands. Predictions from SiBcrop were tested against the observed fluxes and other data (i.e. biomass, LAI, crop yields) at several AmeriFlux eddy covariance flux tower sites with different crop management practices in the US Midwestern region. SiBcrop was able to simulate LAI, biomass, crop yields and carbon fluxes with better seasonality and magnitude, compared to the original SiB model. The new phenology scheme eliminated the need for using remotely sensed NDVI information in predicting carbon and other land-atmosphere exchanges in both rain fed and irrigated croplands. Coupled SiBcrop-RAMS simulations were performed for the Ring2 towers region encompassing Iowa and yielded better results compared to the original SiB-RAMS coupled model. Regional scale SiBcrop-RAMS simulations were also performed for the MCI region and North America in 2007 (SiBcrop being used only in crop areas, at 40 km resolutions). Results from these simulations were encouraging.

As the project ended, a new effort involving use of the model to simulate climate change impacts and the impacts from CO_2 fertilization was being initiated. Two publications and numerous presentations had resulted from the project by its end date, with additional publications in development.

"Evaluating effects of climate changes on Midwest agroecosystems using a climate-crop coupled model" (RFP01). PI Eugene Takle, Iowa State University. Total funding $374,985 for three years.

The overall goal of this project was to understand and quantify how critical ecosystem structure, functioning, and climate feedbacks in major terrestrial ecosystems of the Midwest will change at the regional scale under climate change. Multiple analyses combined with modeling were used to achieve this goal. During the project's three years, the historical climate was analyzed and model projected scenario climates were analyzed to diagnose regional climate change in the Midwestern region. A coupled climate/crop model system was used to project future trends of soil carbon in the region. Main results included: 1) the U.S. Midwest had experienced summer daytime cooling during past decades while global warming was evident; 2) soil organic carbon (SOC) would decrease under the future climate scenarios over this intensive agricultural region; and 3) any uncertainty in absolute SOC would translate directly into its trend, unlike other variables such as temperature whose trends are independent of their values themselves, contrasting the reliability of SOC trend with temperature change.

Research products from this project included: a computer model of simplified quasi-geostrophic 4-layer climate system for studying chaos; a soil carbon and CO_2 budget data set for current and future climates; model-generated trends in surface winds between 1979-2004; and a set of modeling tools for merging global and regional climate model output into ecosystem models such as the CENTURY model. This project contributed to thirteen peer reviewed publications, and supported the graduate studies of one MS student and two PhD students.

"Collaborative research: Assessing long-term plant and soil responses to altered rainfall timing and elevated temperature in grassland ecosystems" (RFP02) and ***"Collaborative research: Assessing long-term plant and soil responses to altered rainfall timing and elevated temperature in grassland ecosystems"*** (RFP05). PIs: John Blair, Kansas State University, and Alan Knapp, Colorado State University. Total funding $604,552 for four years.

This project continued research initiated under the DOE NIGEC program, providing four years of additional support. Objectives were (1) to determine how above- and belowground ecosystem processes respond to increases in ambient temperature and more extreme patterns of precipitation, and (2) to identify the potential consequences of these responses for grassland ecosystem function under an altered climate. To address these objectives, this project expanded and continued a long-term field experiment in which the timing of rainfall events and temperature are simultaneously manipulated in native grassland. The Rainfall Manipulation Plots (RaMPs), initiated in 1997, allowed for manipulation both the amount and the temporal variability in rainfall reaching the plots using clear plastic roofs, which divert natural rainfall and allow for its reapplication at desired amounts and timing. The project is located at the Konza Prairie Biological Station (KPBS), a 3487-ha tallgrass prairie, which is a part of the NSF Long-Term Ecological Research network. In 2003 (with NIGEC support), two 4-m^2 temperature manipulation subplots were installed in all RaMP and non-sheltered reference plots.

Changes in the timing of rainfall events (larger events with longer inter-rainfall droughts), without a change in total precipitation amount, altered soil moisture dynamics, with long-term consequences for soil, plant, community and ecosystem processes. Significant reductions in both plant productivity and soil respiration occurred with more extreme rainfall patterns, contributing to increased potential for N losses. Warming exacerbated the negative effects of altered rainfall timing on plant productivity and soil respiration, presumably due to increased water limitations with elevated temperature. Warming treatments increased soil temperature at 5 cm depth, particularly during spring, fall, and winter. Warming advanced canopy green up in spring, increased winter JCO_2 , and reduced summer JCO_2 and forb ANPP, suggesting that the effects of warming differed in cooler versus warmer parts of the year. It was concluded that (1) major ecosystem processes in the grassland may be substantially altered by predicted changes in interannual climate variability, intra-annual rainfall variability, and temperature, (2) interannual climate variation was a larger source of variation in ecosystem function than intra-annual rainfall variability and warming, and (3) effects of increased growing season rainfall variability and warming were small, but ecologically important. The relative effects of these climate drivers are likely to vary for different ecosystem processes and in wetter or drier ecosystems.

A web page (http://www.konza.ksu.edu/ramps/) was established to facilitate dissemination of information about the experimental approach being used (i.e., RaMP design and operation) and project results. Thirteen peer-reviewed publications had been produced by the end of this projects funding period.

"Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resilience to climate change" (RFP02) and ***"Predicting how CH_4 formation, transport pathways and flux rates in peatlands will respond to climate change"*** (RFP05). PIs: Rod Chimner, Michigan Technological University, and Merritt Turetsky, Michigan State University (RFP02 only). Total funding $504,636 for four years.

This project addressed several fundamental questions regarding the interactive effects of warming and water manipulations on peatland carbon cycling and how they are modified by peat chemistry and vegetation changes. It utilized six sites in Seney National Wildlife Refuge that represent a gradient of long-term water manipulations, plus one site at another peatland in which a short-term warming experiment was conducted. Warming treatment were initiated in the fall of 2008/spring 2008. Results indicated that peatland carbon cycling was influenced by temperature and long term hydrological changes, and further modified by microtopographic landform and vegetation. Warming with IR lamps increased soil and canopy temperatures more than open-top chambers. Overall, warming slightly increased NEE (net ecosystem exchange of carbon) by increasing GPP more than ecosystem respiration (ER). However, plant production varied by species. Leatherleaf decreased, sedge was not affected, and mosses increased CO_2 uptake with warming. Warming also slightly increased CH_4 production. Increasing the water table over a 70 year period increased NEE by lowering ER (Table 2, Figure 4). Higher water table levels also increased CH_4 emissions. Conversely, lowering the water table decreased NEE by increasing ER more than GPP. CH_4 emissions decreased with a decreasing water table level.

The project web page is: http://forest.mtu.edu/faculty/chimner/wetlandlab/carboncycling.htm. This project has resulted in four peer-reviewed publications and supported the research of five MS students and two PhD students.

"Improving prediction of climate change impacts on wetland-rich landscapes: testing model mechanisms with flux-data assimilation at multiple sites" (RFP02). PIs: Ankur Desai, University of Wisconsin, and Scott MacKay, SUNY Buffalo. Total funding $374,694 for three years.

Ecosystem carbon cycle models fail to explain interannual variability in CO_2 fluxes in the upper Midwest. One possible reason is lack of model mechanisms for wetland biogeochemistry and hydrology. Moreover, wetlands are expected to be highly sensitive to climate change. In this project, wetland and regional carbon cycles in a north temperate landscape were studied. A decade long record of wetland flux and micrometeorology was collected and analyzed for climatic controls on wetland NEE. Further, these data were assembled with a regional network of wetland and upland biogeochemical data to quantify the role of wetlands in regional carbon cycling. Together these data were then used to evaluate and constrain a range of ecosystem models using both traditional and Bayesian parameterization and optimization techniques. A decade long record of net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (ER) collected along with water table depth at the Lost Creek shrub fen flux tower revealed complicated seasonal patterns of carbon exchange in face of seasonal and interannual variability in water table elevation. Relatively small interannual variability in NEE was a consequence of relatively large but counterbalancing interannual variability in GPP and ER. Strong coherence in variability in NEE was observed across the sites involved in the study, even though absolute magnitudes in NEE variability varied widely

The project website (http://flux.aos.wisc.edu/twiki/bin/view/Main/LabResearchWetland) includes links to a collaborative wiki where team members can present research results and upload meeting minutes. The data products page has been harmonized with the larger flux tower network and is now located at: http://flux.aos.wisc.edu/twiki/bin/view/Main/ChEASData.

This page contains 30-minute computed fluxes, micrometeorological, biological, ecophysiological, and hydrological data for tall flux tower sites in the region, including the wetland towers supported or analyzed here. Access to powerpoint presentations and publications is also provided via the wiki. Flux tower data has also been sent to the ChEAS, Ameriflux, and Fluxnet teams for further quality assurance and archiving on their databases.

Results from this project led to 16 peer-reviewed manuscripts, supported training of five MS students and two PhD students, and invigorated a new push by the ecosystem modeling community to improve representation of temperate and boreal wetlands in global carbon cycle models.

"How will productivity, evapotranspiration & insect herbivory of the Midwest agroecosystem respond to drought & elevated CO2 anticipated for 2050?" (RFP02). PI: Stephen Long, University of Illinois. Total funding $369,658 for three years.

At over 60 million hectares, the soybean (C_3)-maize (C_4) ecosystem is the largest single ecosystem type in the 48 states and dominates the Midwest. This project examined how projected changes in precipitation and [CO_2] will affect ecosystem C-cycling and water fluxes. Key findings were: (1) contrary to current paradigm, growth of a model C_3 species at elevated CO_2 did not consistently reduce evapotranspiration and increase soil moisture; (2) stomatal sensitivity of a model C_3 species to soil moisture deficit was greater at elevated CO_2 compared to ambient [CO_2]; (3) growth of a model C_4 species at elevated [CO_2] reduced evapotranspiration, conserving soil moisture and ameliorating physiological stress, but did so with insufficient strength or frequency to enhance productivity; and (4) drought reduced susceptibility to herbivory in a model C_3 species grown under elevated CO_2 conditions. Collectively, these results indicate that elevated [CO_2] will ameliorate drought stress effects on both C_3 and C_4 components of the Midwest agroecosystem less than previously assumed.

Results from this project led to three peer-reviewed publications during the project period and supported the training of three PhD students.

"Impacts of historical and future changes in climate and atmospheric CO2 on terrestrial ecosystem structure and functioning in the Midwestern US" (RFP03). PIs: Chris Kucharik, University of Wisconsin, and John Lenters, University of Nebraska, Lincoln. Total funding $362,176 for three years.

The overall objective of this project was to use a Dynamic Global Vegetation Model (DGVM; Agro-IBIS) – which included a detailed representation of agroecosystems – to understand how past and anticipated future changes (1948-2100) in agricultural land management, climate, and atmospheric CO_2 have affected and will affect ecosystem structure and functioning in the Midwest NICCR region. The project focused in particular, on regional-scale carbon, water, and energy cycling. Major steps for the project included: (1) testing Agro-IBIS at two agricultural sites as part of the AmeriFlux network (Bondville, IL and Rosemount, MN), as well as a wetland site in southwestern Nebraska; (2) creating and validating a new, high resolution (~10-km) gridded daily climate dataset across the U.S.; (3) modifying Agro-IBIS to incorporate new high-resolution climate, soils, and vegetation datasets; and (4) completing a series of simulations to study the historical impacts of climate change on natural and managed ecosystems since the late 1940s, including changes in carbon, water, and energy cycling.

The impacts of recent climate change over the 1948-2007 period on potential vegetation of the Upper Midwest U.S. were investigated. Observed total increases in grid cell values of NPP generally ranged from 20–150 g C m^{-2}. Increased summer relative humidity, increased annual precipitation and decreased mean maximum summer temperatures had an influential role in driving these positive trends, likely through the alleviation of soil moisture and heat stress. A total increase in drainage throughout the region, on the order of 20-140 mm yr^{-1}, was observed throughout the study period, driven primarily by increases in annual precipitation. A separate data analysis of the bioclimatic envelopes for plant functional types common to the region revealed no change to the boreal conifer tree climatic domain over the study period, yet did reveal a slightly expanded domain for the temperate deciduous broadleaf tree domain. The location of the Tension Zone, the broad ecotone dividing mixed forests in the north and southern hardwood forests and prairies in the south, was not observed to shift in either the data analysis or during the model simulation. Comparison of Agro-IBIS simulations with evapotranspiration (ET) data collected at a validation site in southwestern Nebraska revealed the need to incorporate groundwater in Agro-IBIS, particularly in riparian zones and other wetland areas that exist throughout the Upper Midwest. Model tests that included an imposed depth-to-groundwater showed significantly improved simulations of ET and soil moisture. Results showed that groundwater can have a significant impact on the surface energy and water balance, and used "depth-to-water-table" was used as an additional forcing variable when considering impacts on the regional energy and water balance.

The project leaders held five Agro-IBIS modeling workshops during 2009-2011 in Madison WI, Ames IA, Lincoln NE, and Minneapolis MN. A global version of the IBIS model continues to be made available at the University of Wisconsin Center for Sustainability and the Global Environment website to outside investigators who wish to check previous published results: http://www.sage.wisc.edu/download/IBIS/ibis.html. The project's findings have been included in sixteen peer-reviewed publications, and three MS students and one PhD student were trained.

"Experimental and modeling study of interactive effects of warming and altered precipitation on function and structure of a tallgrass prairie in the Great Plains" (RFP03). PI: Yiqi Luo, University of Oklahoma. Total funding $388,142 for three years.

The overall objectives of this project were to: (1) to quantify main vs. interactive effects of experimental warming, and added and reduced precipitation on ecosystem processes and community structure and (2) to integrate experimental results into models to improve our ability to predict ecosystem responses to warming and altered precipitation. After collecting two full years of treatment data on a field experiment designed to quantify the main and interactive effects of warming, harvesting, and altered precipitation regime on ecosystem processes and community structure, important differences were found when comparing ecosystem respiration and transpiration from this site, which is dominated by C3 photosynthesis species, to another experimental warming experiment, which is dominated by C4 photosynthesis species, indicating that species composition has significant effects on carbon and water processes.

Warming interacted with halved precipitation to decrease C3 and overall plant production. Modeling analyses indicated that no three-factor interactions were substantial for evapotranspiration, net ecosystem gas exchange, ecosystem respiration, soil respiration, and water use efficiency. However, these effects were not consistent among various ecosystems; and because the latest field data did indicate significant 2- and 3-way interactions on plant productivity, more field and modeling studies are necessary to determine which interactions tend to be significant for which ecosystems.

Information on this experiment is available on the web at: http://bomi.ou.edu/luo. Additionally, the webpage serves as a portal for data sharing at the conclusion of the experiment. Thirty-five research publications were supported by experimental and modeling work conducted by this grant, and a PhD student was trained.

"Agroecosystems: Effects of changes in climate, carbon dioxide, and ozone over the central United States" (RFP03). PIs: Tracy Twine, University of Minnesota, and Andrew Leakey, University of Illinois. Total funding $360,717 for three years.

Terrestrial ecosystem models must be tested before being used to quantify effects of climate change on agroecosystems. This project's goal was to capture the observed response of maize, soybean, and wheat to elevated carbon dioxide concentration, ([CO_2]) and ozone concentration ([O_3]) in the Agro-IBIS model using data from the SoyFACE facility and other published datasets. Simulations then were run for croplands across the Midwest and Great Plains. Elevated [CO_2] led to significant changes in the surface energy budget, with decreases in water loss to the atmosphere and increases in surface heat flux and belowground storage of water. New experimental work discovered that rising [O_3] significantly increased both dark respiration of leaves and the slope (m) parameter of the Ball, Woodrow and Berry model of stomatal conductance. Stimulation of dark respiration at elevated [CO_2] combined with reduced photosynthesis to drive reductions in plant carbon balance and net primary productivity. Changes in stomatal function meant that water use efficiency decreased at elevated [O_3] more than previously assumed. These key physiological responses are now available for driving predictions of how rising [O_3] will alter biogeochemical cycles of the soybean agroecosystem under future elevated [O_3] conditions. Results of a 50-year simulation with the newly parameterized model over the U.S. Midwest show that the response of soybean and maize might have significant impacts on crop yield as well as water and energy budgets at regional scales. Simulations predict decreases in water loss from vegetation to atmosphere that are equivalent to ~ 10% of the mean August rainfall over the most intensively cropped regions of the domain. Annual average decreases over the region are equivalent to 8% of the discharge to the Mississippi River. These results suggest that similar vegetation models that do not vary model parameters under elevated [CO_2] conditions might underestimate future increases in soil water availability and discharge to streams. In addition, the response of agroecosystems to climate variability was examined over the two periods of 1950-2002 and 1982-2002 by minimizing the effects from management and trends in [CO_2], and by focusing on the effects of trends in temperature and precipitation on trends in net primary productivity. Results provided further evidence supporting observational results that suggest 20 - 25% of recent crop yield trends can be explained by changing climate, and suggest that over the past several decades, climate changes have favored increased crop productivity in most agroecosystems of the central U.S. with the exception of winter wheat.

A global version of the IBIS model continues to be made available at the University of Wisconsin Center for Sustainability and the Global Environment website to outside investigators: http://www.sage.wisc.edu/download/IBIS/ibis.html. The project resulted in five peer reviewed publications by its end date and supported the training of two MS students.

"Short and long-term temperature acclimation of roots systems in woody plants and the moderation of warming-induced enhancement of soil CO_2 efflux" (RFP03). PI: Andrew Burton, Michigan Technological University. Total funding $540,387 for four years.

This projects overall objective was to assess the degree to which temperature acclimation occurs in root systems of a variety of woody plants and determine if such acclimation is a short-term, direct physiological adjustment to warmer temperatures (days to months) or a longer term response to changes in nutrient, moisture and C availability, and mycorrhizal status as the ecosystem adjusts to long-term warming (years). If root system respiration does not acclimate to warmer soil, the amount of C respired could increase greatly, leaving less C for other uses, including aboveground growth. To understand both immediate and long-term effects, study sites with 0 to 20 years of experimental soil warming (+5 ^{o}C) were utilized. Temperature acclimation did not occur for specific respiration rates of fine roots (< 1 mm) in response to seasonal changes in soil temperature, but did occur in the first few years of experimental warming in Michigan sugar maple forests. Experimental tests of potential mechanisms suggest that this was due, as least in part, to adenylate control. Through this mechanism, root respiration would be down-regulated to match the work required of the root system for nutrient uptake and assimilation. Dry conditions created by soil warming also significantly affected specific root respiration. In longer-term warming in mixed hardwood forests at Harvard Forest, fine-root specific respiration in warmed soil did not show evidence of thermal acclimation and was much higher than that for control treatments. However, overall carbon allocation to root respiration for soil warming treatments was still constrained, in this case by a large compensating decrease in fine root biomass. This resulting adjustment in ecosystem scale root respiration actually enabled an increase in aboveground productivity. At both study locations, mycorrhizal hyphal respiration and biomass production tended to decrease with soil warming, leading to reduced overall mycorrhizal respiration in warmed soil. Warming caused an initial increase in soil respiration and N mineralization in the Michigan study, which declined rapidly over time. Soil decomposer enzyme activity followed a similar trend. Overall soil fungal and microbial biomass were decreased by soil warming and increased by moisture additions.

A review of vegetation models commonly used as components of earth systems models indicates that only a few allow plant tissue respiration to acclimate to warmer conditions. Many allow respiration to increase exponentially with temperature and do not directly reduce root respiration in drier soil. Based on our consistent findings of constraints on root/mycorrhizal system respiration, model overestimates of the C flux associated with root and mycorrhzial respiration are likely, which could lead to underestimates of future net primary productivity.

The project web site can be found at http://forest.mtu.edu/burtonlab/Warming.html. As data sets are published they are made available on the project page. In addition, data from research at Harvard Forest is available in the data archives on their website (project HF171 under "Long-Term Measurements" at http://harvardforest.fas.harvard.edu/data-archive). Six journal articles were published or in review by the end of the project, with additional manuscripts forthcoming. Three PhD students and two MS students were trained on the project.

"The Interactive effects of elevated temperature and CO2 applied under field conditions on a soybean ecosystem" (RFP04). PI: Carl Bernacchi, University of Illinois. Total funding $245,000 for two years.

The funding provided was used to collect data as part of the Temperature by Free Air CO_2 Enrichment (T-FACE) at the Soybean FACE (SoyFACE) research facility in Champaign, IL over two growing seasons. This experiment investigated the interacting effects of increased canopy temperature (3.5 °C above background) and CO_2 concentration (180 ppm above mean global concentrations) on growth, physiology, and biogeochemical cycling for the soybean-maize agro-ecosystem. The increase in temperature was applied over two entire years using infrared heaters and the CO_2 fumigation during the growing season using FACE technology, with the first year being over *Glycine max* (soybean) and the second year over *Zea mays* (maize). For soybean, results show that elevated temperature decreases and elevated CO_2 increases photosynthesis, growth, and yields for soybean. When applied in combination, the elevated CO_2 + elevated temperature treatment shows no differences in biomass or yields relative to the control. These results suggest that when applied in combination, the benefits of higher CO_2 offset the negative impact of higher temperatures. None of the treatments had an impact on the overall above-ground growth of maize, however, the elevated temperature treatments reduced allocation to reproductive development thereby reducing yields. The elevated CO_2 plot also showed a decrease in yields for maize, likely driven by warmer plant canopies during key reproductive stages resulting from reduced evapotranspiration.

With regard to soil C storage, initially, higher temperatures increase the rate of soil respiration, but this effect is minimized over time. Model predictions of soil heterotrophic respiration using the DAYCENT model reflected accurately only one year of measurements. Frequent measurements of soil respiration showed that, overall, there were no long-term net effects of increased temperature on soil respiration. Further, the disparity between the modeled and measured values shows the need for improved model parameters, which further analysis of the data collected as part of this experiment will provide.

Seven presentations of the results of this project were given and national and international conferences. At the end of the funding period, several manuscripts describing these results were in preparation or in review. In addition, two PhD students were supported by the project.

"Partitioning responses of rhizosphere respiration and soil organic carbon decomposition to warming and altered precipitation in a grassland ecosystem" (RFP04). PI: Weixin Cheng, University of California, Santa Cruz. Total funding $246,273 for two years.

This research project primarily addressed the potential effect of root-soil interactions on the responses of soil organic carbon decomposition to warming and altered precipitation in a grassland ecosystem. Results from a field experiment indicated that the impact of soil warming and altered timing of precipitation on soil CO_2 emissions varied depending on the seasonality. Soil warming generally enhanced total soil CO_2 efflux rate during the growing season, but only significantly so during the fall season. In contrast, delayed precipitation generally reduced the contribution of root respiration to the total soil CO_2 emission, and concurrently enhanced CO_2 emission from microbial decomposition of soil organic carbon during the summer season. Results from lab-controlled experiments demonstrated that root-soil interactions strongly regulated the response of soil organic carbon decomposition to warming. The temperature sensitivity of SOM decomposition when planted with sunflower (*Helianthus annuus*) or soybean (*Glycine max*) was significantly higher than in the same soil when unplanted. Soil warming substantially intensified the rhizosphere priming effect on SOM decomposition (up to 3-fold increase by 5°C warming), thereby increasing the temperature sensitivity of overall soil heterotrophic respiration when roots and rhizosphere processes were active. These results from controlled growth chamber experiments demonstrated that root-soil interactions play a crucial role in shaping the temperature sensitivity of SOM decomposition Based on these findings it is concluded that rhizosphere interactions crucially control soil decomposition processes and concurrently contribute to soil CO_2 emissions.

This project resulted in five peer-reviewed papers describing key results, and two PhD students were supported by the project.

"Quantifying carbon cycle partitioning during climate anomalies using atmospheric carbonyl sulfide (COS)" (RFP05). PI: Elliott Campbell, University of California, Merced. Total funding $112,500 for one year.

The objective of this work was to quantify the net ecosystem exchange (NEE) flux partitioning into gross primary production (GPP) and respiration fluxes during recent Midwest carbon-climate anomalies using simulated and observed airborne measurements of carbonyl sulfide (COS) and CO_2. This objective addresses significant knowledge gaps for regional-scale assessments of carbon-climate feedbacks. Recent work suggests that a COS analysis provides a novel approach for estimating regional flux partitioning for North America. Atmospheric COS and CO_2 observations are useful for flux partitioning because regional gradients in atmospheric CO_2 are dominated by net ecosystem fluxes while regional gradients in atmospheric COS are dominated by GPP-related plant uptake. The scientific merit of the proposed work is a data-driven assessment of regional flux partitioning that is critical for exploring carbon-climate feedback mechanisms and lacking in existing techniques.

The relative vertical gradients of NOAA/ESRL airborne observations in the Midwest growing season (2004-2008) were used to calculate the ratios of GPP to NEE. While growing season COS gradients are dominated by plant uptake, the influence of anthropogenic, soil, and background variation was also accounted for using simulated COS concentrations and background site observations. This study resulted in three deliverables including maps of the regional ratios of GPP to NEE, an analysis of how these ratios vary with carbon-climate anomalies, and a comparison of the regional partitioning based on the COS-CO_2 analysis, local eddy flux data, and terrestrial ecosystem models. These flux partitioning results show similarities between the seasonal trends in the top-down COS analysis that are relatively consistent with diagnostic ecosystem models but reveal errors in models driven by prognostic phenology. The COS-based flux partitioning was consistent with eddy-flux data in regions with relatively homogenous land-cover but differed for heterogenous landscapes. While the COS-analysis suggests a negative correlation between drought and the ratio of GPP to NEE, there was no clear trend in the ecosystem model and eddy flux data.

These results were disseminated through 8 presentations in 2011 including an AGU session that the PI convened, which was the first AGU session to focus on COS as a terrestrical ecosystem tracer. At the one-year project's end, one paper was in review and one in preparation February 2012 as the target submission date for the journal Biogeosciences. The results of this project provided the basis for a new modeling and field project that was funded by DOE/BER.

"Experimental warming effects on soil organic matter dynamics at the temperate-boreal forest ecotone" (RFP05). PI: Sarah Hobbie, University of Minnesota. Total funding $117,500 for one year.

Increased flux of CO_2 from terrestrial soils to the atmosphere in response to climate warming represents a potentially important positive feedback to climate change. In this project, measurements of *in situ* warming effects on soil respiration were combined with mechanistic experiments to determine how the dynamics of warming effects on soil respiration are influenced by warming-induced changes in the soil microbial community; soil drying; and changes in decomposer use of labile versus recalcitrant soil organic matter (SOM) pools at the southern boreal-temperate forest ecotone. Continued measurements of *in situ* soil respiration indicate that warming by 4°C has enhanced respiration by 18% and 25%, respectively, in 2009 and 2010. A set of three laboratory experiments were begun in 2011, designed to help to elucidate the role of changes in the soil microbial community; carbon substrate depletion; and soil drying on soil microbial respiration (data were forthcoming at the project's end date).

When this one-year project ended, one manuscript was in review and one PhD student had been supported.

Collective Publications List and Project Websites for NICCR RFP-05 Projects
NICCR Midwestern Regional Center

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Reich: Main BioCON experiment site at http://www.biocon.umn.edu/index.html and Water Experiment at http://www.biocon.umn.edu/water_experiment.html

Collective Publications List and Project Websites for NICCR RFP-03 Projects
NICCR Midwest Regional Center

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http://www.sage.wisc.edu/download/IBIS/ibis.html

Burton: project website: http://forest.mtu.edu/burtonlab/Warming.html

Collective Publications List and Project Websites for NICCR RFP-02 Projects
NICCR Midwest Regional Center

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Project Websites

Blair and Knapp: A web page (http://www.konza.ksu.edu/ramps/) was established to facilitate dissemination of information about the experimental approach being used (i.e., RaMP design and operation) and project results-to-date.

Chimner and Turetsky:
Project website: http://forest.mtu.edu/faculty/chimner/Research/NICCR.htm

Desai and Mackay:
Project website: http://flux.aos.wisc.edu/twiki/bin/view/Main/LabResearchWetland . Links on this page include our collaborative wiki where team members can present research results and upload meeting minutes. A data products page is at: http://flux.aos.wisc.edu/data/wetland/ . This page contains 30-minute computed fluxes, micrometeorological, hydrological data for the wetland tower sites, and will also eventually contain model results.

Collective Publications List and Project Websites for NICCR RFP-01 Projects
NICCR Midwest Regional Center

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Project Websites:

Curtis, Vogel, Dragoni: We continue to post NEE, ancillary meteorological data and comprehensive biological data from our control site (the UMBS AmeriFlux site) to the Fluxnet data site at CDIAC. This posting is current through 2006. http://www.biosci.ohio-state.edu/~pcurtis/UMBS~Flux/index.htm.

Reich: Information for the project entitled: "Interactive Effects of Carbon Dioxide, Water, and Nitrogen on Grassland Ecosystem Processes" is posted at the BioCON website: http://www.biocon.umn.edu/

Tackle, Pan: Information for the project entitled: "Evaluating effects of climate changes on Midwest agroecosystems using a climate-crop coupled model" is posted at: http://www.eas.slu.edu/People/ZPan/proj_NICCR06-09.htm

**Collective Publications List and Project Websites for Inherited NIGEC projects
NICCR Midwestern Regional Center**

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Wayson,C.A., J.C. Randolph, P.J. Hanson, H.P. Schmid, and C.S.B. Grimmond. 2006. Comparison of soil respiration methods in a mid-latitude deciduous forest. Biogeochemistry 80:173-189.

Project Websites:

Blair: A web page was established to facilitate dissemination of information about the experimental approach being used (i.e., RaMP design and operation) and project results-to-date. http://www.konza.ksu.edu/ramps

Bolstad**:** Our data are maintained and distributed via the ChEAS website, at the Pennsylvania State University, Department of Meteorology. These include the processed and gap-filled flux data, site micrometeorology, and site characterization and biometric measurements. http://cheas.psu.edu

Kucharik: A global version of the IBIS model continues to be made available at the SAGE website to outside investigators who wish to check previous published results: http://www.sage.wisc.edu/download/IBIS/ibis.html

Schmid: Measurements at MMSF~Flux have been ongoing since March 1998. Annotated data summaries (1998 – 2006) are available through the Fluxnet database http://www.daac.ornl.gov/FLUXNET

Appendix

Final Reports to the MRC of Projects Funded under RFP01 to RFP05 and NIGEC projects receiving their final year of funding from the NICCR MRC.

Final Report to Midwestern Regional NICCR, January, 2012

Peter B. Reich
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Interactive effects of carbon dioxide, water, and nitrogen on grassland ecosystem processes

Principal Investigator: Peter B. Reich, University of Minnesota, preich@umn.edu, 612-624-4270
Co-investigator: Sarah Hobbie, University of Minnesota

1. Abstract.

Our research focuses on how inputs of water to terrestrial ecosystems interact with atmospheric CO_2 and soil nitrogen (N) supply to affect ecosystem structure and function. Our experiment uses free-air CO_2 enrichment, soil N additions, and precipitation removal (using portable rain-out shelters) to expose open-grown established experimental grassland plots to all combinations of two levels of each factor. Using NICCR funding we built 24 portable rain-out exclosures, each 2 x 2 m in area, which were employed periodically from May 10 – August 15 in 2007, 2008, 2009, 2010, and 2011 to remove approximately 40-45% of the rainfall during that period in each year. We measured soil moisture, soil CO_2 flux, leaf gas exchange, biomass production and other response variables on plots that represent numerous replicates of each unique CO_2, N and water treatment combination. Results from 2007-2011 demonstrated a number of responses to water, nitrogen, and CO_2.

2. Research activities.

Our overarching hypothesis is that water shortage and low N supply are fundamental constraints on the response of NPP to elevated CO_2 (eCO_2) such that NPP shows little response to eCO_2 under either low water or N availability. We hypothesize that reduced stomatal conductance caused by eCO_2 will increase soil moisture, but much more so during intermediate moisture conditions than during wet or extremely dry conditions. Thus the degree of increase of NPP by eCO_2 will depend upon on the relative magnitude of water savings from decreased canopy-level water loss at eCO_2, but simultaneously also on the relative limitation of NPP caused by lack of water. As a result, eCO_2 might compensate for mild water limitation but would likely be of modest impact when water limitations were severe.

To address these questions we established a new factorial experiment by incorporating manipulations of precipitation into an ongoing global change field experiment of atmospheric CO_2 and simulated atmospheric N deposition in a temperate perennial grassland experiment at the Cedar Creek research site in Minnesota. We used free-air CO_2 enrichment, soil N additions, and precipitation removal (using portable rain-out shelters) to expose open-grown established experimental grassland plots to all combinations of two levels of each factor. This experiment utilized 48 plots, each 2 x 2 meters, all planted with 9 species randomly chosen from a set of 16 species in 1997. The plots included six replicates of all eight combinations of ambient and elevated CO_2, ambient and enriched N supply, and ambient and diminished precipitation. The latter treatments were new in 2007 (all others began in 1998). Our water treatments—an ambient ($AmbH_2O$) and a reduced precipitation ($LowH_2O$) regime—were designed to assess the general questions of how changes in water availability influence ecosystem processes and of whether water availability alters ecosystem response to *e*CO_2 (across two levels of N supply), using treatments that represent current and projected climate scenarios for Minnesota. To implement these treatments we designed and built 24 portable rain-out shelters that remove almost all rainfall (≈95-98%) from a given 2 x 2 meter plot when they are in place (Fig. 1). The rainout shelters cover entire individual plots and consist of removable shelters that fit over permanent frames situated around the outside of each plot. The shelters have a slanted roof and four individual sidewalls. There are gaps below the roof and above and below the sidewalls to allow considerable air flow. The roof is made of clear corrugated polycarbonate over a PVC frame and the sidewalls are of clear polyethylene film stretched over light-weight wooden frames. To prevent runoff into adjacent plots, intercepted rain is channeled using gutters, and moved well outside each of the six ≈60-plot rings.

Fig 1. One of the 24 portable rain-out shelters temporarily in position.

The protocol was to put the shelters into place immediately prior to ≈45% of significant rainfall events between May 10-August 15 (there were 15 such events/summer, ≥ 5mm rain, on average during this period over the 1900-2005 year period), and remove them after the completion of these events. In the case of predicted nighttime precipitation, shelters were left in place until sunrise when they are removed. This precipitation-modification regime proved successful. Shelters were in place much less than 1% of the time (nearly always under cloudy conditions and rarely during midday) and cumulatively reduce integrated PPFD (mid-May to mid-August) by ≈0.05% (1/2000th).

We routinely measured soil moisture and soil CO_2 flux at approximately 1-2 week intervals during the growing season. Measurements of leaf gas exchange were made for four or five species in replicate plots of all eight combinations of CO_2, N and water treatments. Aboveground and belowground biomass measures were taken on all plots in June and August every year. *Pinus strobus*, *Quercus macrocarpa* and *Q. ellipsoidalis* seeds were planted each spring.

3. Research highlights.

Results from the five years of the study (2007-11) supported our broad hypothesis that complex interactions depending on soil moisture status may be common, but did not strongly support most of our specific hypotheses. Additionally, analyses that include the 2011 data are still in process, so final understanding of results across the full five years are not yet available in most cases.

Leaf level gas exchange. In 2007-10 (2011 data not yet analyzed), light-saturated net photosynthesis (*A*) was moderately stimulated by *e*CO_2 and to a similar extent in the *Amb*H_2O and *Low*H_2O treatment (measurements taken when soils were at least partially dry)(Fig. 2). Stomatal conductance was reduced across treatments as expected (-25%, CO2 p = 0.0754) however to a lesser extent under lowH2O and elevated N (CO2xNxH2O p=0.1064) compared to other treatment combinations. This response was consistent across species (Fig. 3).

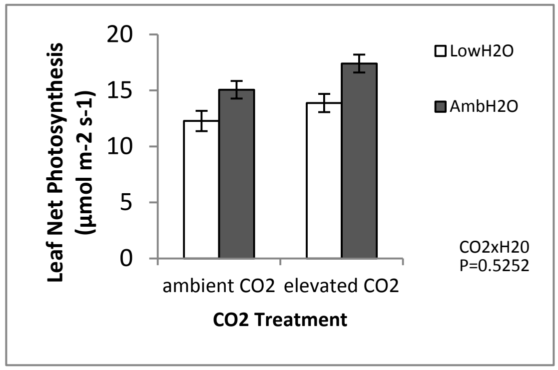
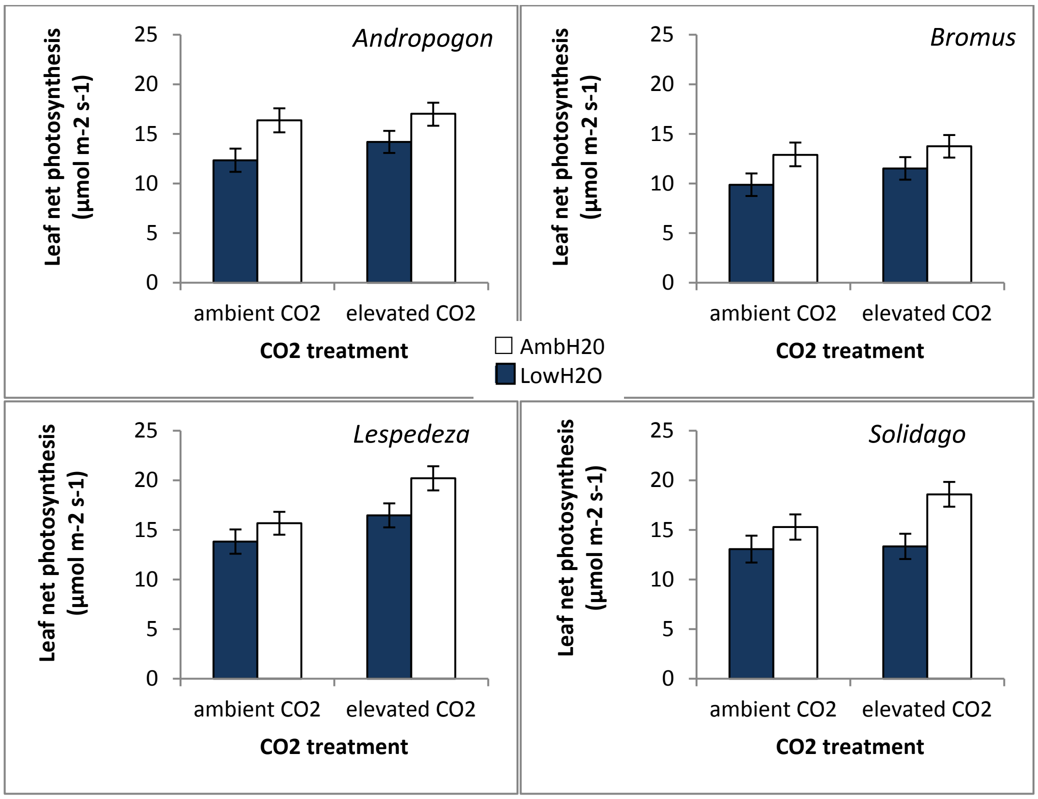


Fig 2. Leaf net photosynthetic responses to all combinations of water and carbon dioxide treatments, pooled across years. Reductions in photosynthesis in response to lower water availability were similar at both ambient and elevated CO_2 (no CO2xH2O interactions) Responses to water treatment were significant ($P<0.0001$) and similar across species and years ($P>0.13$). Elevated CO2 did not significantly increase net photosynthetic rates compared to at ambient CO2 (CO2 effect P=0.1673).



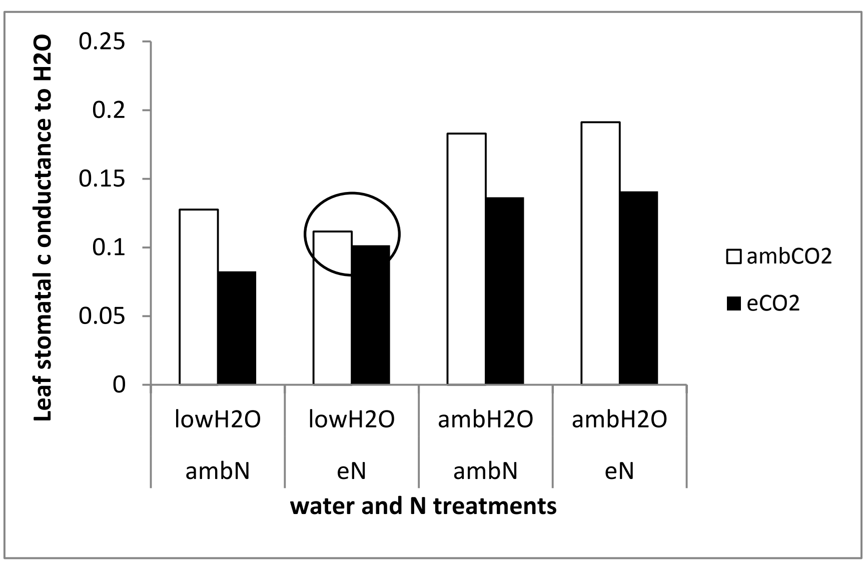


Fig 3. eCO2 induced reductions in mean leaf stomatal conductance at each water and N level (pooled across years and species)

One goal of this study was to test the hypothesis that any eCO2-induced increase in photosynthesis would be greater in the lowH2O than the ambH2O treatment when soil water deficits are modest compared to wet or dry conditions. Our preliminary results show rather that eCO2 induced stimulation of net photosynthesis increases as soil conditions become drier (Fig. 4)

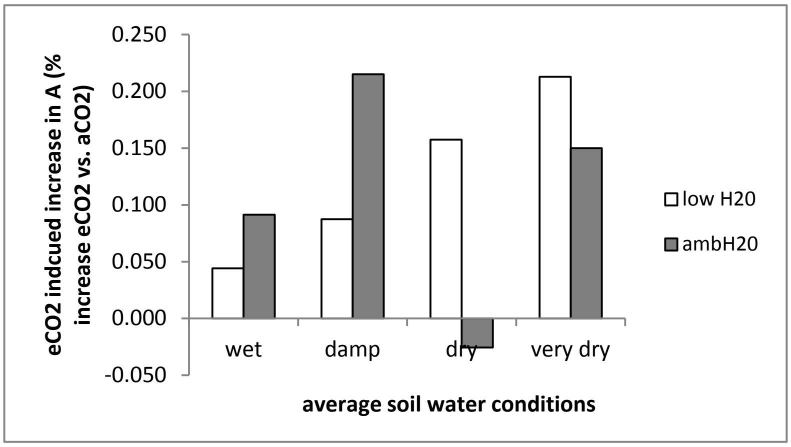


Fig 4. Magnitude of eCO2 induced increase in net photosynthesis across soil water conditions categorized across treatments as wet (%>7), damp(5-7%), dry(3.5-5%), very dry(%<3.5) (CO_2 x H2O x condition p=0.2820.

Leaf samples have been sent out for 15N analyses, from which we will determine the interactive effects of eCO2, reduced H2O and elevated N on symbiotic N2 fixation by the legumes in this study.

Biomass. Over the 2007-2011 period, there was a three-way interaction between CO_2, N and water treatments (P=0.0034) on aboveground biomass; such that when both water and N supply were at their lower levels, the response to elevated CO_2 disappeared (see red circled bars); whereas at treatments where one or both of water and N were at their higher respective levels, there was a strong positive CO_2 or effect (Fig 5.). This strongly suggests that when soil resources are at limiting supply the CO2 fertilization effect on biomass production will be reduced, or even eliminated, casting doubt on the main models using the IPCC assessment which continue to assume (i.e. built into model algorithms) large increases in biomass production due to rising atmospheric CO2 concentrations. We submitted a paper with the four-year results to Science, but this was not accepted for publication. We are near to submitting a manuscript (Reich, Hobbie, and Lee, submitted) to Nature with the five year results.

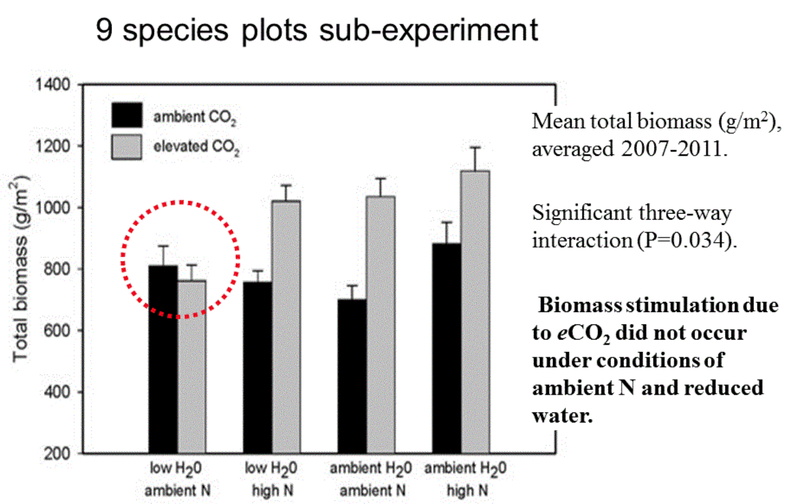


Fig. 5 Interaction between CO_2, N and water treatments on aboveground biomass

Additionally, on average from 2007-2011, the root fraction (total root biomass as fraction of total plant biomass) was increased by the "low-water" treatment at low levels of both CO and N (in the ambientCO2 treatment and ambient N treatment levels), consistent with the notion of increased root allocation towards a limiting resource. However **this response was reversed at** enriched levels of N and CO_2 (Fig. 6). This interaction was only marginally significant overall (P=0.11).

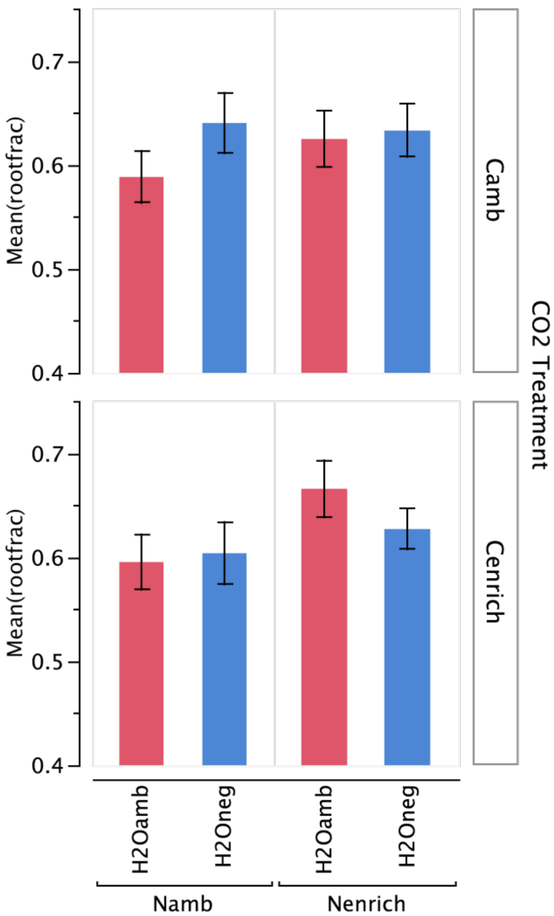


Fig 6. Fraction of biomass in roots (root biomass/total biomass) on average across all combinations of CO2, N, and water treatments.

Germinant and seedlings establishment.

Here we describe results at the end of the 2011 field season. In 2009 complete lack of precipitation for 5 weeks post planting resulted in 100% lack of emergence of those planted that spring, highlighting the need for at least minimal water availability regardless of *e*CO2. By the end of 2011, oaks (pooling bur and red) planted in 2007 and 2008 were more numerous and larger (diameter and height) in eCO2 than ambient CO2. CO2 effects on those planted in 2010 and 2011 were minimal. For those planted in 2007 and 2008 (both bur and red), individuals surviving to end of 2011 were fewer in low water treatment but larger. Water treatments did not significantly influence numbers or size of oaks surviving to end of 2011 for those planted in 2010 or 2011. For N, the main impact was for both species in 2008, fewer survived to the end of 2011 under enriched than ambient N, and those that did were smaller as well.

For both water and N, it is possible that higher soil resources increase herbaceous production and competitively suppressing oak seedling growth, as surviving seedlings tended to be smaller in the higher soil resource treatments. Further analyses are being made to investigate these trends.

New research investigating temporal changes in soil microbial communities was begun with collaborators from University of Oklahoma**.** In this study, we are monitoring temporal changes in soil microbial communities and investigating the dynamic of their response to rising CO2, N deposition and precipitation. Analyses are still in process.

In 2010 and 2011 visiting scholar Dr. Nico Eisenhauer, from J.F. Blumenbach Institute of Zoology and Anthropology, University of Goettingen, Germany, investigated soil organisms. The interacting factors manipulated in the NICCR-supported sub-experiment (CO_2, N inputs, and precipitation) are hypothesized to influence soil community structure and function in complex ways. All three factors alter the quantity and quality of resources entering the soil system, thereby controlling not only the composition and but also the functioning of soil biota. Despite the increasing appreciation that the consequences of impending global change can be better understood if varying agents are studied in concert, there is a paucity of multi-factor long-term studies, particularly on belowground processes. Thus, we addressed this gap by examining the responses of soil food webs and biodiversity to enrichment of CO_2, elevated N and summer drought. We used structural equation modeling (SEM), various abiotic and biotic explanatory variables, and data on soil microorganisms, protozoa, nematodes and soil microarthropods to identify the impacts of multiple global change effects on drivers below ground. We found that changes in CO_2 and N availability resulted in modest alterations of soil biotic food webs and biodiversity *via* several mechanisms, encompassing soil water availability, plant productivity and – most importantly – changes in rhizodeposition (Fig. 7). Manipulation of summer drought exerted surprisingly minor effects, only detrimentally affecting belowground herbivores, and ciliate protists at elevated N. Elevated CO_2 increased microbial biomass and the density of ciliates, microarthropod detritivores and gamasid mites, most likely by fuelling soil food webs with labile C. Moreover, beneficial bottom-up effects of elevated CO_2 compensated for detrimental elevated N effects on soil microarthropod taxa richness. By contrast, nematode taxa richness was lowest at elevated CO_2 and elevated N. Thus, enrichment of atmospheric CO_2 concentrations and N deposition may result in taxonomically and functionally altered, potentially simplified, soil communities. Detrimental effects of N deposition on soil biodiversity underscore recent reports on plant community simplification. This is of particular concern as soils house a considerable fraction of global biodiversity and ecosystem functions

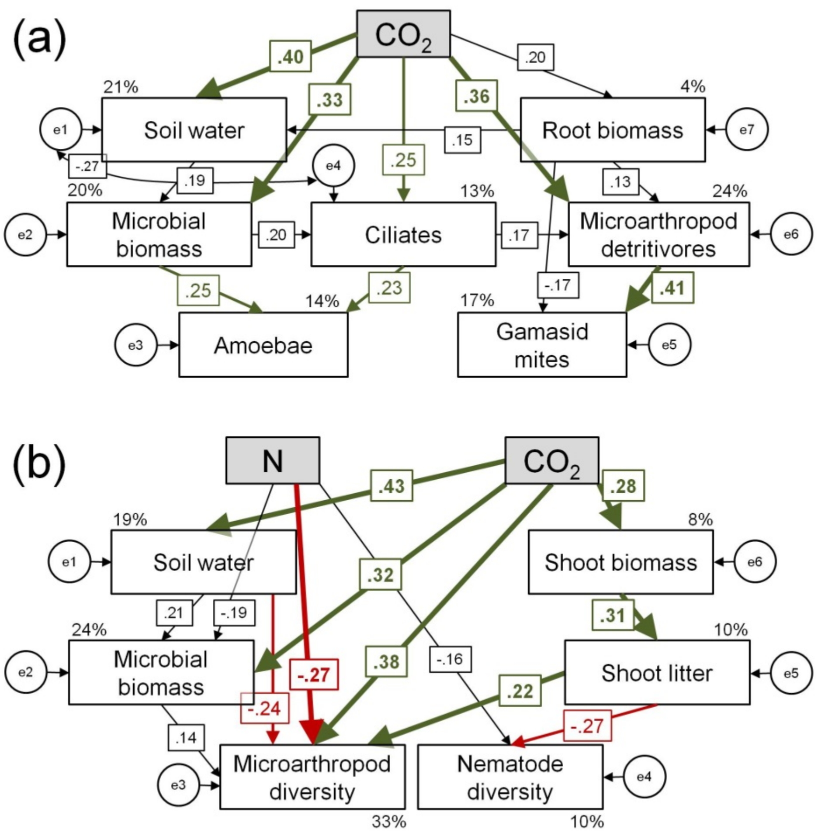


Fig 7. Structural equation models of global change effects on soil biota in secondary successional grassland in Minnesota, USA. (a) Causal influences of elevated CO2 (exogenous variable; gray rectangle) on soil water content, root biomass productivity, microbial biomass, and abundance of soil animals (endogenous variables; white rectangle). (b)Causal influences of elevated N and CO2 (exogenous variables) on soil water content, shoot biomass productivity, shoot litter,microbial biomass, and taxa richness of soil microarthropods and nematodes (endogenous variables; white rectangle

4. Publications (required).

Adair, EC, PB Reich, SE, Hobbie, J Trost. 2011. Elevated CO_2 stimulates grassland soil respiration by increasing carbon inputs rather than by enhancing soil moisture. Global Change Biology: First published online : 28 JUL 2011, DOI: 10.1111/j.1365-2486.2011.02484.x

Eisenhauer, N, S Cesarz, R Koller, K Worm, PB Reich. Global change below ground: impacts of elevated CO2, nitrogen and summer drought on soil food webs and biodiversity. Global Change Biology (in press).

Reich, P.B. and SE Hobbie. Decade-long persistence of nitrogen constraints on the CO_2 fertilization of plant biomass. Proc Natl Acad Sci (in review)

Reich, P.B., SE Hobbie, TD Lee. Joint effects of water and nitrogen limitation eliminate CO2 fertilization of plant production. Nature (to be submitted)

Reid, JP, EC Adair, SE Hobbie, PB Reich. Biodiversity, nitrogen deposition and CO2 affect grassland soil carbon cycling but not storage (Ecosystems, tentatively accepted).

Main BioCON experiment: http://www.biocon.umn.edu/index.html
Water Experiment: http://www.biocon.umn.edu/water_experiment.html

FINAL REPORT, 2009-2011. DISTURBANCE, SUCCESSION AND FOREST CARBON DYNAMICS: A LARGE-SCALE MANIPULATION AT THE UNIVERSITY OF MICHIGAN BIOLOGICAL STATION.

Principal investigator: Peter S. Curtis, Ohio State University
Co-Investigator: Gil Bohrer, Ohio State University
Co-Investigator: Christopher M. Gough, Virginia Commonwealth University
Co-Investigator: Knute J. Nadelhoffer, University of Michigan

1. Abstract

Our objective was to of uncover mechanisms behind shifts in carbon (C) cycling in response to disturbance, ecological succession, and ongoing climate change across the Upper Great Lakes Region. In 2008, we implemented the Forest Accelerated Succession Experiment (FASET) by stem girdling all aspen and birch within 39 ha in northern lower Michigan. Ecological, meteorological, and remote sensing measurements were used to quantify effects of climate, species composition, and canopy structure on the forest C cycle. There was a modest decrease in net ecosystem CO_2 exchange in the treatment area two years following disturbance, and although this treatment response was subtle, there was a cascade of biogeochemical changes that promoted functional resilience in the C cycle. There was near-complete retention of actively-cycling soil nitrogen and rapid replacement of senescing species' leaf area as soil N availability increased and was reallocated to new leaf area of later-successional trees. Long-term resilience of C storage to disturbance was found to be dependent upon canopy structural reorganizations that enhance carbon uptake. Our improved understanding of how forests work is enhancing science-based products, including models, that will inform land managers and policy makers how to manage forests in the backdrop of local and global environmental change.

2. Research activities

Our overarching, long-term hypothesis is that forest net ecosystem production (NEP) across much of the Upper Great Lakes Region will increase following transition from aspen-dominated ecosystems to those of later-successional species with biologically and structurally more complex canopies (Figure 1, Nave et al. 2011). At the end of our final year of funding, we are congruent with the timeline of activities described in our proposal. That is, 1) Quantifying changes in C and N cycling following implementation of FASET and characterizing forest canopy structure; 2) Publishing/submitting peer-reviewed manuscripts; 3) Contributing to FLUXNET synthesis activities and; 4) Participating in new and ongoing collaborative projects that use FASET as a research platform.

We have tested the short-term hypothesis that disturbance due to senescence of early successional species will decouple C and N cycles by decreasing belowground C allocation, increasing soil N availability and leaching, but that this decoupling will be temporary due to a mechanism for functional resilience: a rapid increase in N uptake and compensating growth by the residual canopy. We link our short- and long-term hypotheses by predicting that re-coupling of C and N cycles along a new trajectory following the loss of early-successional species will interact with changes in canopy structure to determine the eventual extent of NEP recovery.

We found that inter-annual patterns of growing season net ecosystem exchange (NEE) in the control and treatment areas diverged two years following girdling, with NEE declining in the treatment footprint and increasing slightly in the control forest during 2009 (Figure 2, Nave et al. 2011). Treatment area NEE was 0.6 Mg C ha^{-1} yr^{-1} higher than that of the control forest during the 2007 and 2008 growing seasons, exhibiting little change from one year to the next. In contrast, treatment area NEE declined from growing season 2008 to 2009 by 9 % while concurrently increasing in the control area by 4 %, resulting in near convergence of disturbed and control NEE in 2009. Although dormant season NEE, which was dominated by ecosystem respiration, was consistently more negative in the treatment area than in the control area, year-to-year shifts in treatment and control NEE from 2007 to 2009 were parallel and suggest no treatment effect outside of the growing season. The reduction in growing season NEE in the treatment area from 2008 to 2009 was caused by steeper declines in gross primary production than in ecosystem respiration (Nave et al., 2011).

We found that canopy species diversity is a critical determinant of net primary production (NPP) resilience to disturbance. Ecological theory and observation suggest that more species diverse ecosystems will exhibit greater resiliency of NPP in the face of disturbance because of enhanced niche partitioning. Our study is one of the first to use long-term, continuous C cycling data to show that the trajectory of declining NPP in maturing, unmanaged forests is attenuated when the canopy comprises a diverse assemblage of early and middle successional species (Figure 3, Gough et al., 2010). The mechanism for attenuated declines, or in rare circumstances increases, in NPP was the release of intact middle successional maple, oak, and pine species that proliferated leaf area index (LAI) as stem mortality of early successional aspen and birch increased. Greater canopy diversity likely buffered NPP from a precipitous decline that might occur in a low diversity stand that becomes abruptly defoliated following senescence.

We also found that variation in canopy structural complexity helped explain differences in wood NPP across the UMBS forest landscape. We showed that rugosity, the variability of three-dimensional arrangement of photosynthetic surface area within the canopy, is as important as other well-known stand-level drivers of aboveground production including LAI, site quality, and stand age (Figure 4, Hardiman et al., 2011). Our findings suggest that a more structurally complex canopy will drive higher rates of forest production in similar forest types despite mortality of large numbers of early-successional canopy trees. Recruitment of shade-adapted subdominant cohorts into the canopy may have additive effects on forest productivity with canopy structural complexity by increasing total leaf area and light use efficiency at low light levels. Given the extent of forests undergoing this successional transition in the Upper Great Lakes, an increase in NPP caused by increasing canopy structural complexity will have important implications for regional C storage by allowing forests to remain net C sinks as they mature.

To summarize, we used experimental and long-term observational approaches to elucidate mechanisms promoting biogeochemical resilience in a changing forest (Figure 5, Nave et al., 2011). Our experimental disturbance simulated natural processes that target the early-successional canopy dominants, decreasing belowground C allocation but allowing for efficient redistribution of actively cycling N away from these senescing early-successional species to later-successional trees. Because the senescence induced by experimental disturbance was diffuse over space and time, the forest avoided the large N losses that cause C storage to decline following severe disturbances. The fact that our subtly disturbed forest has thus far avoided this intervening 'biogeochemically depauperate' period suggests it is on a track towards biogeochemical reorganization much sooner, and with a greater share of actively cycling N still intact than if it had been severely disturbed.

Looking to the future, we hypothesize that the changes in N cycling and uptake by later-successional trees that have emerged during this disturbance phase have shifted the N cycle to a fundamentally different, faster track—one which will interact with increasing canopy complexity over successional time to increase the rate of C storage by this forest (Figure 1). Structurally complex forest canopies with multiple layers and many canopy gaps are more efficient at intercepting light than are more structurally simple ones and thus may contribute to higher C uptake. Ongoing studies at our site indicate that stands with increased canopy structural complexity and N availability, including those approaching 200 years-old, have higher rates of C storage. Together the biogeochemical and structural changes following our experimental disturbance may form a mechanistic basis for recent studies that show forests are capable of storing C for centuries, redefining our understanding of the biogeochemical functioning and ecosystem services provided by later-successional forests.

3. Research highlights

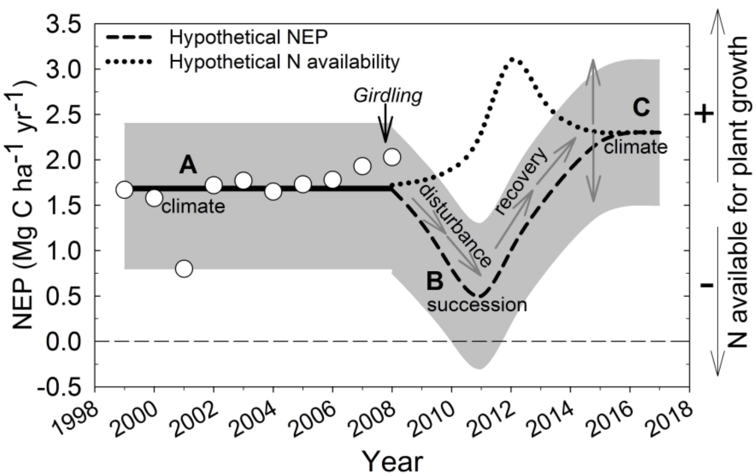


Figure 1. Measured and hypothetical NEP and N availability at UMBS before and following aspen and birch decline. [A] Current NEP varies inter-annually due to climate. [B] A period constrained by disturbance and recovery follows aspen and birch mortality. [C] Short-term increases in N availability and allocation to the canopy persist into successional time, allowing diversification of canopy structure and an increase in average annual NEP, which is once again constrained by climate.

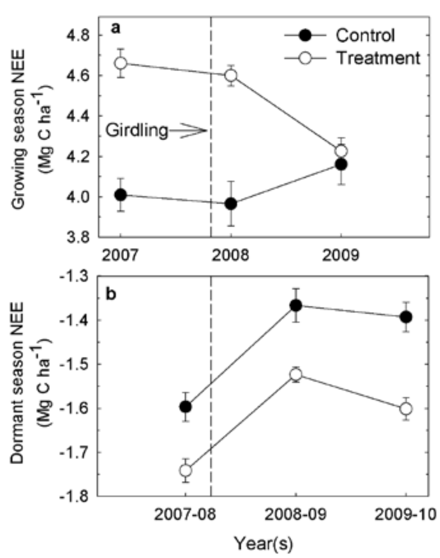


Figure 2. Net ecosystem CO_2 exchange [NEE] in the control and treatment meteorological tower flux footprints during the growing [a] and dormant seasons [b] before and following the girdling of mature aspen and birch, 2007-2009.

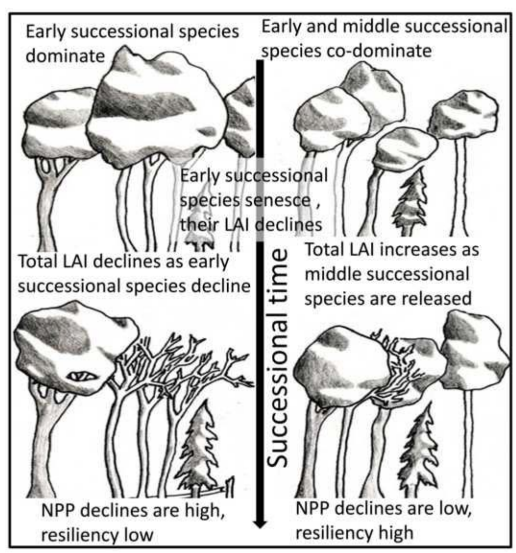


Figure 3. Mechanisms that constrain trajectories and resiliency of wood NPP as forest composition transitions from early successional aspen and birch to middle successional oak, maple, and pine species.

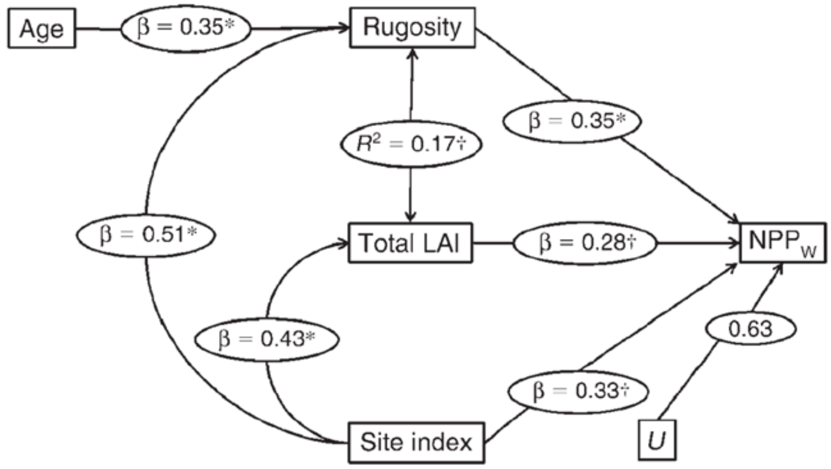


Figure. 4. The relative contributions of stand age, site index, total leaf area index (LAI), and rugosity on annual wood net primary production (NPP_W). Unidirectional arrows indicate significant and direct effects with path strength indicated by standardized partial regression coefficients (β). Bidirectional arrows indicate correlation with path strength indicated by a coefficient of determination (R^2). U indicates the contribution of unmeasured variables. * P , 0.05; †P , 0.1.

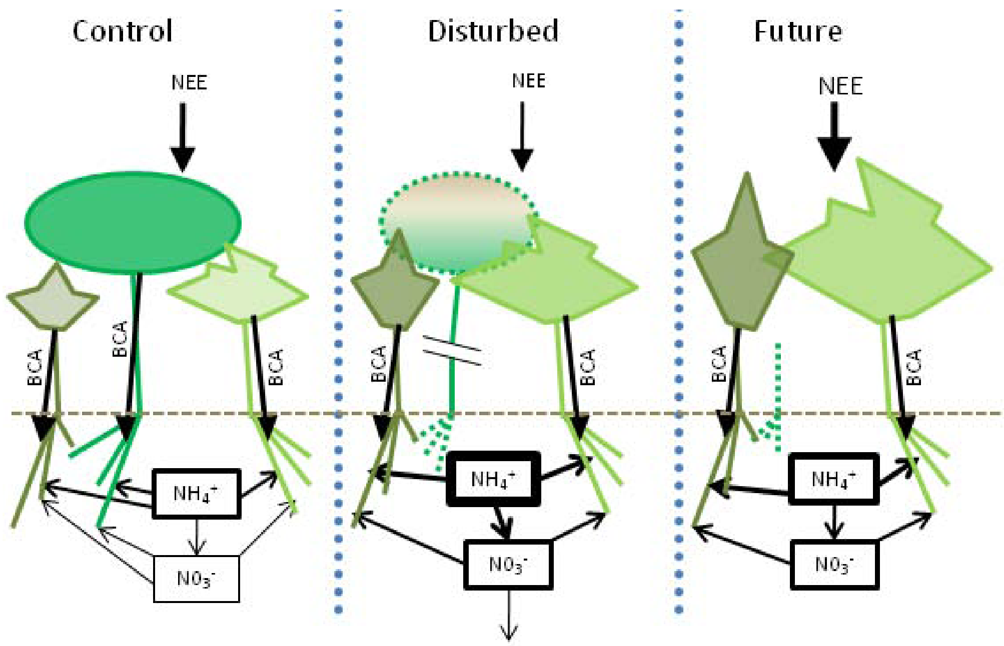


Figure 5. Conceptual diagram of key fluxes pre- and post-treatment, and during future forest succession. Arrows represent C and N fluxes. Arrow widths correspond to relative flux rates. Belowground boxes represent soil inorganic N pools, with frame thicknesses corresponding to the availability of the N compounds. Decreased belowground C allocation [BCA] during disturbance prevents early-successional species from taking up N, increasing NH_4+ availability, nitrification, and NO_3- leaching. These N cycling changes prompt increased N uptake, canopy growth and diversification by later successional trees, responses which are self sustaining over successional time and result in the next sere of this forest having greater rates of C uptake [NEE].

4. Research products

We continue to post NEE, ancillary meteorological data and comprehensive biological data from our tower cluster site (the UMBS AmeriFlux control site and the FASET disturbance site) to the Fluxnet data site at CDIAC. This posting is current through 2010. Our project web site, listing many meta-data and biometric data is at: http://www.biosci.ohio-state.edu/~pcurtis/UMBS~Flux/index.htm.

Our site continues to encourage numerous synergist activities with other investigators and the funding of new proposals to further a mechanistic basis for changes in C fluxes during forest succession. Remaining project funds will be used to re-instrument the now dormant Ameriflux tower at the Sylvania Wilderness Preserve, initiating major new collaborations with researchers at the University of Wisconsin, the University of Minnesota, and the Woods Hole MBL Ecosystems Center. Other ongoing collaborations are:

***Ecosystem Modeling*:**

- *Improving process-level understanding of the factors underlying long-term trends and year-to-year variability in carbon sequestration of northeastern forests*. Drs Andrew Richardson (Harvard Univ.), William Munger (Harvard Univ.), Peter Curtis (PI), Gil Bohrer (co-PI) Danilo Dragoni (Indiana U.), David Hollinger (USDA Forest Service, NH), Ongoing, NOAA support
- *Improving modeling projections of forest NPP via incorporation of dynamic mortality and canopy structure algorithms into the Biome-BGC-MV model.* Drs. Christopher Gough (PI, Virginia Commonwealth Univ.) and Ben Bond-Lamberty (Co-PI, DOE Battelle Joint Global Change Research Institute). Pre-proposal to be submitted to NSF (Jan 9, 2012).
- *Modeling disturbance, climate change and land use decisions effects on northern Great Lakes forest carbon cycling using the LANDIS-II model.* Drs. Ankur Desai (Univ. Wisconsin) and Robert Scheller (Portland State Univ.) Ongoing, NSF IGERT support.

Atmospheric Chemistry:

- *Changes in biogenic VOC emissions due to forest disturbance and their impact on tropospheric photochemistry.* Drs. Steven Bertman (Western Michigan Univ.), Tom Jobson (Washington State Univ.) and Brian Lamb (Washington State Univ.). Recently concluded, NSF support.
- *Modeling the effect of high-resolution land-surface heterogeneity and forest structure on emission, chemistry, and dispersion of volatile organic compounds and reactant species.* Dr. Gil Bohrer (co-PI) and PhD student William Kenny (OSU). Ongoing support from NASA Earth and Space Science Graduate Training Fellowship

Carbon and nitrogen cycling:

- *Above and belowground C and N cycle linkages during forest succession.* Drs. Knute Nadelhoffer (PI) and Lucas Nave (Postdoc- Univ. of Michigan). Ongoing, NSF support.
- *Enriched Background Isotope Study (EBIS): Application of an Ecosystem-scale ^{14}C Tracer to Soil-Carbon-Cycle Studies.* Dr. Paul Hanson (ORNL) and others. Ongoing, DOE support.
- *Changes in NO_y fluxes following forest disturbance.* Dr. Jed Sparks (Cornell Univ.). Ongoing, UM support.
- *Oxidized carbon and nitrogen exchanges through the seasonal snowpack at UMBS and their contribution to the annual ecosystem gas exchange budget.* Dr. Detlev Helmig and PhD student Brian Seok (Univ. of Colorado). Recently concluded, NSF IGERT support.
- *Spatiotemporal Variation in Greenhouse Gas Fluxes from Forest Soils: Earthworms as modulators of soil-atmosphere CO_2, CH_4, and N_2O exchange.* Dr. Knute Nadelhoffer and PhD student Jasmine Crumsey (Univ. of Michigan). Ongoing, NSF IGERT, NSF Dissertation Improvement Grant, and UM support.
- *Root distribution in response to disturbance and succession; investigations using Ground Penetrating Radar.* Dr. John Butnor (USDA Forest Service). Ongoing, OSU, UM, FS support.

- *LTREB: Drivers of forest C storage from canopy closure through successional time.* Knute Nadelhoffer (PI, University of Michigan) and Lucas Nave (Co-PI, University of Michigan), Pre-proposal to be submitted to NSF (Jan 10, 2012).
- *N cycling, tree competition, and C uptake during multiple phases of forest development.* Lucas Nave (PI, University of Michigan) and Knute Nadelhoffer (Co-PI, University of Michigan). Pre-proposal to be submitted to NSF (Jan 9, 2012).

Phenology:

- *Forest phenology network.* Dr. Andrew Richardson (Harvard Univ.)**.** Ongoing, NSF support.

Hydrology:

- *Linking heterogeneity of above-ground and subsurface processes at the gap-canopy patch scales to ecosystem level dynamics. Drs. Gil Bohrer (co-PI) and Valeriy Ivanov (Univ. of Michigan) and Mehta Moghaddam (Univ. of Michigan). Ongoing, NSF support.*
- *Resolving interactions between canopy structure, roots, disturbance history, and soil moisture heterogeneity Drs. Gil Bohrer (co-PI) and Valeriy Ivanov (Univ. of Michigan). Proposal submitted to NSF*
- *Cosmos probe validation. Dr Jim Shuttleworth, Marek Zreda, Xubin Zeng and Chris Zweck (Univ. of Arizona), Ongoing NSF support*

Remote Sensing of canopy structure and function:

- *Aerial spectral analysis of canopy structure.* Dr. Peter Curtis (PI) and student Brady Hardiman (Ph.D., OSU). Recently concluded, NCALM and NSF IGERT support.
- *Developing optically derived canopy physiological and structural parameters for the estimation of vegetation productivity.* Dr. Lee Vierling and PhD student Steve Garrity (Univ. of Idaho). Recently concluded, NSF IGERT support.
- *Incorporating Effects of Remote-Sensed Tree-Scale Structural Heterogeneity of Forests on Flux Exchanges and Atmospheric Surface Layer Properties.* Dr. Gil Bohrer (co-PI) and PhD student Kyle Maurer (OSU). Recently concluded, NSF IGERT support.
- *Incorporating the effects of tree-scale land-surface heterogeneity on litter moisture for use in regional models of wildland fire dynamics and fire risk.* Dr. Gil Bohrer (co-PI) and PhD student Anthony Bova (OSU).Recently concluded, NASA Earth and Space Science Graduate Training Fellowship.

Community composition and demography

- *Mapping and identifying controls on plant community composition following disturbance.* Dr. Deborah Goldberg, UM support

5. Publications (site-level*; PI/co-PI bold)

We have 20 peer-reviewed publications during the 2009-2011 reporting period, 9 from site-level work and 11 from collaborative engagements within Fluxnet.

Richardson A.D., Anderson R.S., Arain M.A., Barr A.G., **Bohrer G**., Chen G., Chen J.M., Ciais P., Davis K.J., Desai A.J., Dietze M.C., Dragoni D., Garrity S.R., **Gough C.M.,** Grant R., Hollinger D.Y., Margolis H.A., McCaughey H., Migliavacca M., Monson R.K., Munger J.W., Poulter B., Raczka B.M., Ricciuto DM, Sahoo A.K., Schaefer K., Tian H., Vargas R., Verbeeck H., Xiao J. and Y. Xue. 2012. Terrestrial biosphere models need better representation of vegetation phenology: Results from the North American Carbon Program site synthesis. *Global Change Biology* (in press, available on-line).

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Lee X., Goulden M.L., Hollinger D.Y., Barr A., Black T.A., **Bohrer G**., Bracho R., Drake B., Goldstein A., Gu L., Katul G., Kolb T., Law B.E., Margolis H., Meyers T., Monson R., Munger W., Oren O., Paw U K.T., Richardson A.D., Schmid H.P., Staebler R., Wofsy S. and L. Zhao. 2011. Observed increase in local cooling effect of deforestation at higher latitudes. *Nature* 479:384–387.

*Garrity S.R., **Bohrer G.,** Maurer K.D., Mueller K.L., Vogel C.S. and **P.S. Curtis**. 2011. A comparison of multiple phenology data sources for estimating seasonal transitions in forest carbon exchange. *Agricultural & Forest Meteorology* 151:1741–1752.

Yuan W., Luo Y., Liu S., Yu G., Zhou T., Bahn M., Black A., Richardson A.D., Desai A.R., Cescatti A., Marcolla B., Jacobs C., Chen J., Aurela M., Berhnofer C., Bielen B., **Bohrer G.,** Cook D.R., Dragoni D., Dunn A.L., Gianelle D., Grünwald T., Ibrom A., Leclerc M.Y., Lindroth A., Liu H., Marchesini L.B., Montagnani L., Pita G., Rodeghiero M., Rodrigues A., Starr G. and P.C. Stoy. 2011. Redefinition and global estimation of basal ecosystem respiration rate. *Global Biogeochemical Cycles* 25:GB4002, doi:10.1029/2011GB00415.

Niu S, Luo Y, Fei S, Montagnani L, **Bohrer G**, Janssens I, Gielen B, Rambal S, Moors E, Matteucci G. (2011) Seasonal hysteresis of net ecosystem exchange in response to temperature change: patterns and causes. *Global Change Biology* 17, 3102-3114.

*Hardiman, B. S., **G. Bohrer, C.M. Gough**, C.S. Vogel, and **P.S. Curtis**. 2011. The role of canopy structural complexity in wood net primary production of a maturing northern deciduous forest. Ecology 92: 1818-1827.

*Nave L.E., **Gough C.M**., Maurer K.D., **Bohrer G**., Hardiman B.S., Le Moine J., Munoz A.B., **Nadelhoffer K.J**., Sparks J.P., Strahm B.D., Vogel C.S., **Curtis P.S.** 2011. Disturbance and the resilience of coupled carbon and nitrogen cycling in a northern temperate forest. Journal of Geophysical Research – Biogeosciences 116:G04016, doi:10.1029/2011JG001758

Xiao, J., Zhuang, Q., Law, B.E., Baldocchi, D.D., Chen, J., Richardson, A.D., Melillo, J.M., Davis, K.J., Hollinger, D.Y., Wharton, S., Oren, R., Noormets, A., Fischer, M.L., Verma, S.B., Cook, D.R., Sun, G., McNulty, S., Wofsy, S.C., Bolstad, P.V., Burns, S.P., **Curtis, P.S**., Drake, B.G., Falk, M., Foster, D.R., Gu, L., Hadley, J.L., Katul, G.G., Litvak, M., Ma, S., Martinz, T. A., Matamala, R., Meyers, T.P., Monson, R.K., Munger, J.W., Oechel, W.C., Paw, U. K.T., Schmid, H.P., Scott, R.L., Starr, G., Suyker, A.E., Torn, M.S. 2011. Assessing net ecosystem carbon exchange of U S terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. Agricultural and Forest Meteorology 151: 60-69.

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6. Student degrees supported

There have been six PhD students and five MS students supported in whole or in part by this project. They are:

- Brady Hardiman (PhD), Department of Evolution, Ecology, and Organismal Biology, The Ohio State University. Anticipated degree date, June 2011.
- Jennifer Goedhart (MS), Department of Evolution, Ecology, and Organismal Biology, The Ohio State University. Graduated, June 2010.
- Kellen Calinger (PhD), Department of Evolution, Ecology, and Organismal Biology, The Ohio State University. Anticipated degree date, June 2014.
- Kyle Mauer (PhD), Department of Civil and Environmental Engineering and Geodetic Sciences, The Ohio State University. Anticipated degree date, June 2014.
- David Meehan (MS), Biology Department, Virginia Commonwealth University. Anticipated degree date, May 2012.
- Conor Flynn (MS), Natural Resources Graduate Program, The Ohio State University. Anticipated degree date, June 2012.
- Alex Fotis (PhD), Department of Evolution, Ecology, and Organismal Biology, The Ohio State University. Anticipated degree date, June 2016.

- Jasmine Crumsey (PhD), Department of Ecology and Evolutionary Biology, University of Michigan. Anticipated degree date, June 2013
- Susan Cheng (PhD), Department of Ecology and Evolutionary Biology, University of Michigan. Anticipated degree date, June 2015
- Dekel Shlomo (MS), Department of Civil and Environmental Engineering and Geodetic Sciences, The Ohio State University. Graduated September 2011.
- Liel Naor-Azrieli (MS), Environmental Sciences Graduate Program, The Ohio State University. Anticipated degree date, December 2012.

Land-Atmosphere Exchanges Across the Midcontinental Region of North America: Processes, Scaling, and Evaluation

A. Scott Denning and Keith Paustian

Colorado State University – Final Report

Award Number: MTU 050516Z14

Project Abstract: Croplands are important man-made ecosystems. The majority of the US cropland area is concentrated in the Midwest, which has the highest uptake of carbon dioxide (CO_2) during the growing season of crops; overall, croplands encompass about one fifth of the total US land area. Since most of the decisions are made by humans, croplands are a good test bed for studying and analyzing the anthropogenic influence on the global and regional carbon cycle and land-atmosphere CO_2 exchanges. We have used a coupled land-atmosphere modeling system (SiBcrop-RAMS) in analyzing the regional scale carbon and other exchanges across the croplands in continental North America, subject to interannual variability of weather, management, and existing and expected changes in climate across the continent.

Development of a new, fine resolution crop model (i.e. SiBcrop; Lokupitiya et al., 2009) and coupling it with RAMS (a regional atmospheric model developed at Colorado State University; Pielke et al., 1992), was one of the major achievements of this project. Originally the land surface model named Simple Biosphere (SiB; Sellers et al., 1986; 1996a; 1996b) model, did not have a good representation of the dynamic events and growth stages associated with the managed cropland ecosystems. Therefore we incorporated a crop specific phenology and physiology scheme within SiB and developed SiBcrop, to further improve prediction of carbon and other land-atmosphere exchanges in croplands. Predictions from SiBcrop have been tested against the observed fluxes and other data (i.e. biomass, LAI, crop yields) at several AmeriFlux eddy covariance flux tower sites with different crop management practices in the US mid western region. The coupled SiBcrop-RAMS simulations were performed for the recently established Ring2 towers region encompassing Iowa; the coupled SiBcrop-RAMS modeling system yielded better results compared to the coupled original SiB-RAMS coupled model. Regional scale SiBcrop-RAMS simulations have also been performed for the MCI region and North America in 2007 (SiBcrop being used only crop areas, at 40 km resolutions). Preliminary results from these simulations are encouraging). We have also used the model to simulate climate change impacts or the impacts from CO_2 fertilization. This work is still being continued, and currently some preliminary results are available at site level.

Project Activities:

Overall Project objectives:

- Improve the functionality of the coupled atmosphere-biosphere modeling system, SiB-RAMS by incorporating the dynamics of agroecosystems through development of crop-specific phenology and physiology schemes.

- Testing the improved offline model for specific sites, perform high-resolution simulation of Intensive Observing periods using the fully coupled SiBccrop-RAMS model.

- Evaluation of the simulations from the fully-coupled model against airborne transects of eddy covariance measurements, atmospheric trace gas distributions, and cropland carbon inventory measurements made by other investigators involved in the Mid Continent Experiment.

- Develop high resolution vegetation and other maps for the MCI region.

Project progress:

Evaluation of the performance of original SiB over croplands, code and parameter modification for better simulation of croplands

Original SiB model was not specifically designed for cropland ecosystems, and there were certain drawbacks in simulating the specific events and growth processes relevant to croplands, which are managed ecosystems. For instance, crop rotation, specific developmental stages, harvest events, etc., were well not represented. Therefore the code and certain parameters were modified for better simulation of crops. This was done as a project component during the first year.

Development and coupling of crop specific phenology and physiology models with SiB

Originally SiB has used remotely sensed NDVI information in deriving leaf area index (LAI) and fraction of photosyntheically active radiation (fPAR) in estimating photosynthesis, respiration and other land-atmosphere exchanges. However, LAI based on NDVI had a remarkable deviation in terms of seasonality and magnitude compared to the obsereved LAI in the field. Therefore, development of crop specific phenology models for predicting LAI and carbon fluxes, and coupling those models with SiB to develop a new fine resolution crop model (SiBcrop; Figure 1) was a major project component. So far we have developed crop specific phenology and physiology models for crops having both C3 (soybean, and wheat), and C4 (corn) physiologies. Corn and soybean phenology models were developed and coupled to SiB during the year 1 of the project. However, further testing and refining of the coupled SiB-phenology scheme for these crops (the new model termed SiBcrop) has been an ongoing process.

SiBcrop was run to simulate the presence of corn and soybean in several Ameriflux eddy covariance flux tower sites (i.e. Bondville, IL, Mead, NE (both rain fed and irrigated sites), and Rosemount, MN, Ames, IA, etc.), using the meteorological forcing from 6-hourly NCEP-DOE Reanalysis 2 (Kalnay et al., 1996) weather data. The new model, remarkably improved the prediction of the CO_2 fluxes (sub hourly, diurnal, and seasonal; Figure 2) and LAI (Figures 3 and 4) compared to the original model, which had LAI prediction based on remotely sensed NDVI. In addition SiBcrop closely predicted the yields and biomass in different plant pools, as observed at the AmeriFlux field sites (Figure 5).

During the second year of the project, a phenology and physiology scheme for winter wheat was developed within SiBcrop. Crop specific parameter values were added and a phenology scheme corresponding to different growth stages and specific growth requirements by winter wheat, such as vernalization prior to reproductive, was developed. These specific events and growth stages were set based on growing degree-days and a crop-specific carbon allocation scheme, the same way as in the phenology and physiology scheme for the other crops within the model. The predicted carbon fluxes from the winter wheat simulations by SiBcrop were compared against the Ameriflux eddy covariance flux tower sites with winter wheat (Figures 3 and 4). Site level performance of SiBcrop for these major crops was further tested during the third year of the project, by participating in the NACP site interim synthesis activities, in which the comparisons were made against the site-specific observations and the predictions from several other land surface models.

Regional scale runs of coupled SiBcrop-RAMS

The coupled SiBcrop-RAMS simulations were performed for the recently established Ring2 towers region encompassing Iowa (Corbin, 2009; Miles, 2009; Fig. 6). The spatial distribution of corn and soybean in the Ring2 domain was prescribed according to a crop coverage map derived by Hansen et al. (2008) from high-resolution satellite vegetation data. We aggregated the 56-m imagery to a 1 km grid, and computed area fractions for each crop on a 10 km simulation grid. The SiBCrop model was called separately for each crop in each grid cell, and their contributions were weighted by fractional area to obtain grid-cell mean fluxes of energy, water, momentum, and CO2. The model was run over most of North America on a coarse 40-km grid, with a 10-km “nested grid” over the MidContinent region. The coupled SiBcrop-RAMS modeling system yielded better results compared to the coupled original SiB-RAMS (Fig. 6). The comparison of SiBcrop-RAMS simulations on the Ring 2 tower region was made against the calibrated CO_2 mixing ratio measurements by the NOAA Environmental Science Research Laboratory, Global Monitoring Division (formerly CMDL), and Ken Davis and his team at Penn State University (Figure 6).

Regional scale SiBcrop-RAMS simulations have also been performed for North America in 2007 (SiBcrop being used only for crop tiles, at 40 km resolution). The latter regional scale simulations were also used for the MCI synthesis, which compares top-down and bottom-up approaches for estimating regional scale carbon exchanges. Preliminary results from these simulations are encouraging, with significant improvement in the predicted carbon uptake by croplands during the summer time. These latter regional level simulations were performed during the third year of the project.

Research highlights

- SiBcrop has been able to simulate LAI, biomass, crop yields and carbon fluxes with better seasonality and magnitude, compared to the original SiB model. The new phenology scheme eliminated the need for using remotely sensed NDVI information in predicting carbon and other land-atmosphere exchanges in both rain fed and irrigated croplands.

- SiBcrop has been successfully coupled with RAMS, and the results from the simulations over the Ring 2 tower region has shown remarkable improvements in predicting carbon fluxes.

- Further testing of corn and soybean phenology scheme over several AmeriFlux eddy covariance flux tower was carried out.

- The phenology scheme for winter wheat was developed and evaluated against the observations at the AmeriFlux sites having wheat crop.

- A continental scale evaluation of carbon fluxes and biomass production by SiBcrop-RAMs system, with the input of 40-km scale crop maps for corn, soybean, and wheat has been performed for the year 2007.

- SiBcrop performance was further tested by participating in the MCI- and site interim-syntheses and regional scale analyses under the NACP, to further evaluate its performance against both observations and other models.

- During the 3-yr project period, the following presentations were made at the conferences/annual meetings on the outcome of the project:

  - Lokupitiya, E. Denning, S., Paustian, K., Baker, I., and Schaefer, K. 2007. Coupling crop specific phenology models with the Simple Biosphere Model (SiB) to improve the Land-Atmosphere Exchanges Across the US Midcontinental Region. Poster presentation at AmeriFlux meeting, Boulder, CO, held on Oct 17-18, 2007.

  - Lokupitiya, E. Denning, S., Paustian, K., Baker, I., and Schaefer, K. 2007. Using crop phenology models with SiB for improved prediction of carbon fluxes across the mid continental region of North America. Oral presentation at the Fall AGU meeting, San Francisco, CA, held on Dec 10-14, 2007.

  - Lokupitiya, E. Denning, S., Paustian, K., Baker, I., and Schaefer, K. 2008. Predicting cropland carbon fluxes using SiBcrop. Oral presentation at chEAS meeting, Wisconsin, held on Aug 11-14, 2008.

  - Lokupitiya, E., Denning, S., Paustian, K., Corbin, K., Baker, I., and K. Shaefer. 2008. Evaluation of the performance of SiBcrop model in predicting carbon fluxes and crop yields in the croplands of the US mid continental region. 41st Annual meeting of the American Geophysical Union. December 15-19, 2008, San Francisco, California, USA.

  - Lokupitiya, E., Denning, S., Paustian, K., Corbin, K., Baker, I., and K. Shaefer. 2009. Prediction of carbon fluxes and crop yields using SiBcrop. North American Carbon Program Joint Workshop on Site-level Interim Synthesis, Regional and Continental Interim Synthesis. January 07-09, Oak Ridge National Laboratory, Tennessee, USA.

- Lokupitiya, E., Denning, S., Paustian, K., Corbin, K., Baker, I., and K. Shaefer, M. Hansen, K. Pittman. 2009. Simulation of carbon fluxes and prediction of crop yields within MCI region using SiBcrop. Second NACP (North American Carbon Program) All investigators meeting. February 17-20, San Diego, California, USA

- Lokupitiya, E., Denning, E. Paustian, K. Baker, I., Corbin, K., Shaefer, K., and A. Schuh. 2009. Estimation of carbon cycling in croplands using SiBcrop model. International Symposium on Soil Organic Matter Dynamics: Land Use, Management and Global Change. July 6-9, 2009, Colorado Springs, Colorado, USA

- Lokupitiya, E., Denning, E. Paustian, K. Baker, I., Corbin, K., Shaefer, K., and A. Schuh. 2009. Response of Carbon Fluxes in US Croplands to Changing Climate. 8th International Carbon Dioxide Conference. September 13-19, Jena, Germany.

- **Papers published**:

  - Lokupitiya, E., Denning, S., Paustian, K., Baker, I., Schaefer, K., Verma, S., Meyers, T., Bernacchi, C.J., Suyker, A., and M. Fischer. 2009. Incorporation of crop phenology in Simple Biosphere Model (SiBcrop) to improve land-atmosphere carbon exchanges from croplands. Biogeosciences, 6, 969-986.

  - Lokupitiya, E., Denning, S., Paustian, K., Baker, I., Schaefer, K., Verma, S., Meyers, T., Bernacchi, C.J., Suyker, A., and M. Fischer. 2009. Incorporation of crop phenology in Simple Biosphere Model (SiBcrop) to improve land-atmosphere carbon exchanges from croplands. Biogeosciences Discussions, **6**, 1903-1944.

Planned activities for the future:
We submitted a proposal for 1-year extension of this project, to develop fine resolution (1 km) crop maps for multiple years (2003 onwards), using the crop area information available at the National Agricultural Statistics Service (NASS) county level data and fine resolution (56 m) AWiFS crop images produced by the cropland datalayer of NASS, for performing SiBcrop-RAMS simulations on crop tiles across North America at 40 km resolution. Interannual variability of Carbon exchanges would have been studied. Predicted CO_2 mixing ratios would have been compared against the calibrated measurements from the network of tall tower measurements managed by NOAA. NICCR declined to support this work.

Other ongoing activities
Integration of agro-ecosystem modeling and analysis in the NACP Midcontinent intensive experiment in the future will be supported by NASA.
Studying the impact of climate change
It has been predicted that the current ambient CO_2 concentration will be doubled towards the latter half of the 21st Century. There is significant uncertainty associated with how the agricultural ecosystems would respond to such changes in CO_2 and anticipated climate change

impacts. Therefore we have also used SiBcrop model to simulate any impacts of CO_2 fertilization based on potential future climate change, anticipating that the outcome of our efforts will contribute towards improving knowledge on the subject. Given the differences in their anatomy and physiology, the response of C3 and C4 crops to CO_2 fertilization are different, as found in the chamber and FACE experiments. Elevated concentrations of CO_2 (compared to current levels) would cause enhanced rates of photosynthesis and reduced stomatal conductance. Although vast majority of C3 plants are known to show both these responses, C4 plants consistently show only reduced stomatal conductance, while the photosynthetic response is still debatable (Leaky et al., 2009). We envisage studying any differential response of C3 and C4 plants under several potential future climate change scenarios incorporating doubled CO_2 concentration, elevated temperature, and changes in precipitation. We adjusted the C3 physiology to incorporate the changes in specific leaf area and foliar total non-structural carbohydrates (Wand et al., 1999), to accommodate for the impact from increased CO_2 concentration. This work is still at preliminary stage, and only preliminary results are available at site level (Figure 7).

Further development of the model

In addition to incorporating additional crops (alfalfa, sorghum, rice), we also plan to further modify the respiration calculation in the model, using a simple microbial decomposition model. Total ecosystem respiration includes both autotrophic (plant) and heterotrophic (soil microbial) respiration. In original SiB, autotrphic respiration included canopy maintenance respiration, calculated based on a fraction of the maximum Rubisco Velocity (V_{max}), and a temperature based Q_{10} function. In SiBcrop, we replaced the half hourly autotrophic respiration calculation in SiB, with the growth and maintenance respiration calculation in the crop phenology and physiology scheme (Lokupitiya et al, 2009). We are further modifying the heterotrophic/soil respiration in SiBcrop, to incorporate decomposition scheme of litter and soil carbon pools. The heterotrophic respiration calculation in SiBcrop allows for the decomposition of litter left on the ground due to senescence and harvest removal. We have incorporated more realistic fractionation of aboveground and belowground litter among the ten soil layers, and more realistic distribution of root fractions for separate C3 and C4 crops.

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Wand , S.J.E., Midgley , G.F., Jones, M.H., and Curtis, P.: Responses of wild C4 and C3 grass (Poaceae) species toelevated atmospheric CO2 concentration: a meta-analytic test of current theories and perceptions. Glob Change Biol, 5, 723-741, 1995.

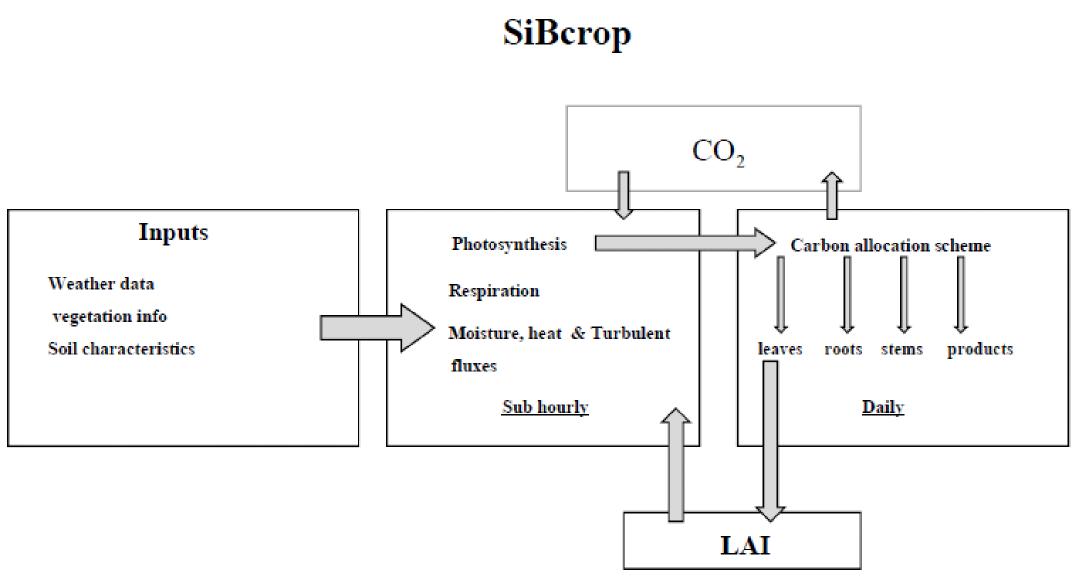


Figure 1. Basic methodological framework of SiBcrop model

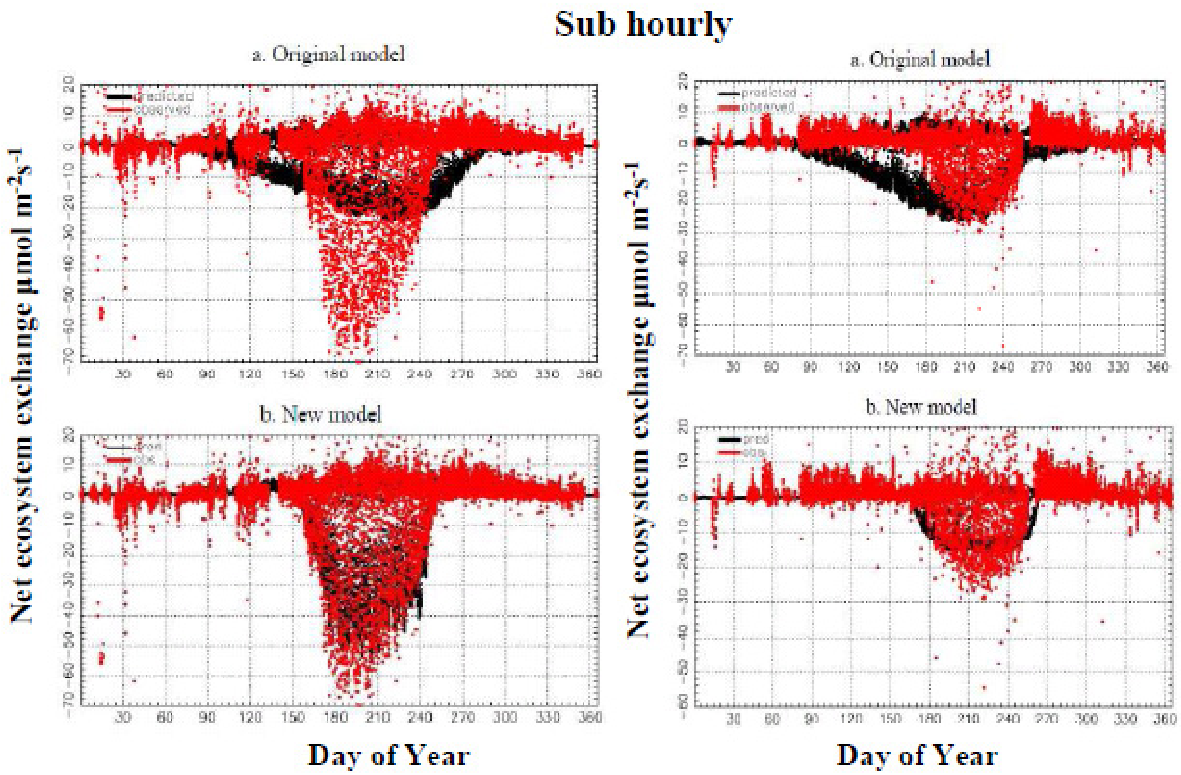
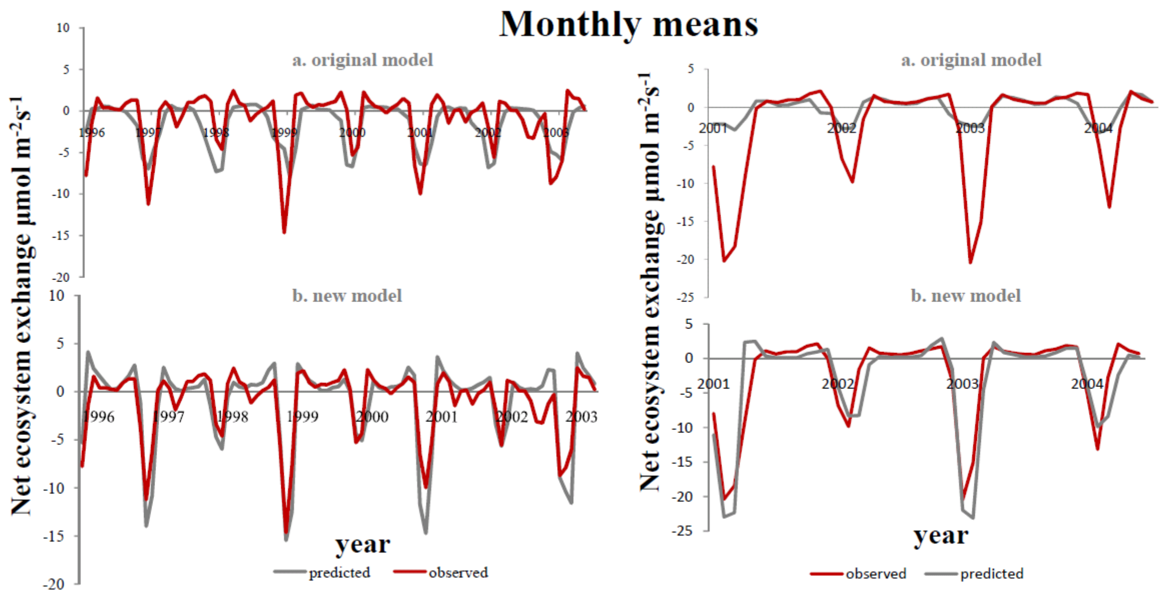
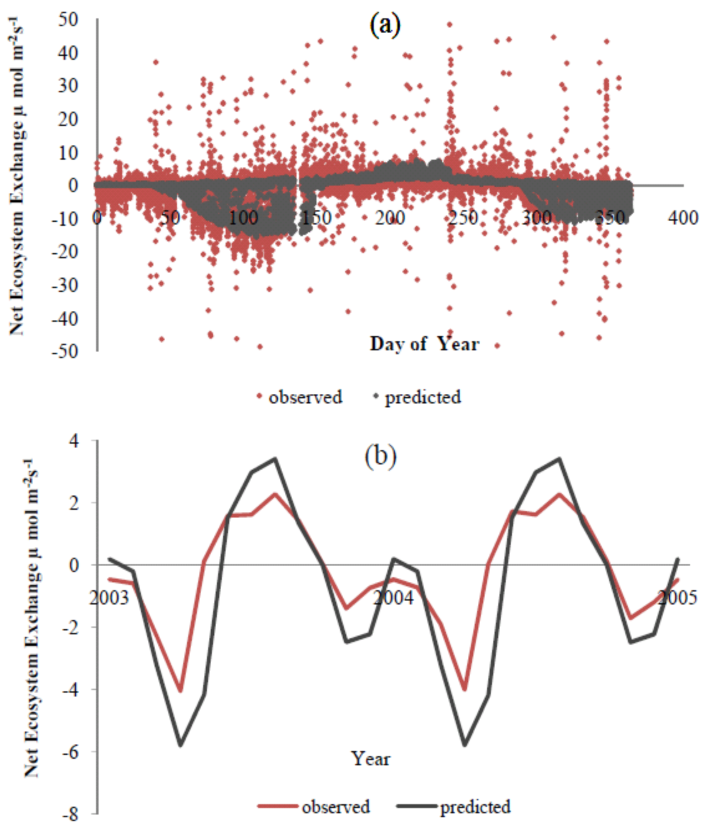


Figure 2. Net ecosystem exchange comparison of original model (SiB) against the new model (SiBcrop). Sub hourly NEE for corn (top left) and soybean (top right) in Bondville and monthly means of NEE for Bondville (bottom left) and Mead rain fed site (bottom right) showing the alternating presence of corn (odd numbered years) and soybean (even numbered years) in the field.





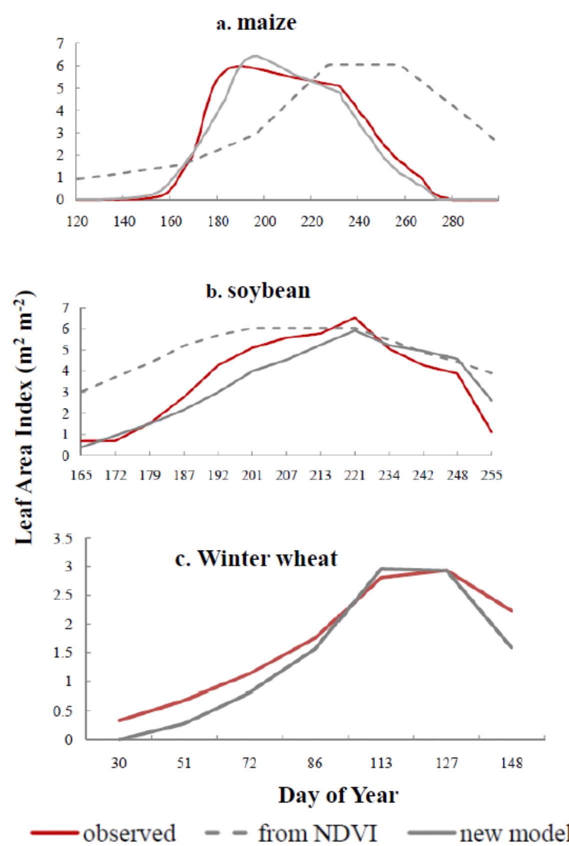


Figure 3. Net ecosystem exchange for winter wheat at ARM-SGP site: (a) sub hourly NEE in 2003, and (b) interannual NEE based on

Figure 4. Some LAI curves for maize (Bondville in 1999), soybean(Bondville in 2000), and winter wheat (ARM-SGP in

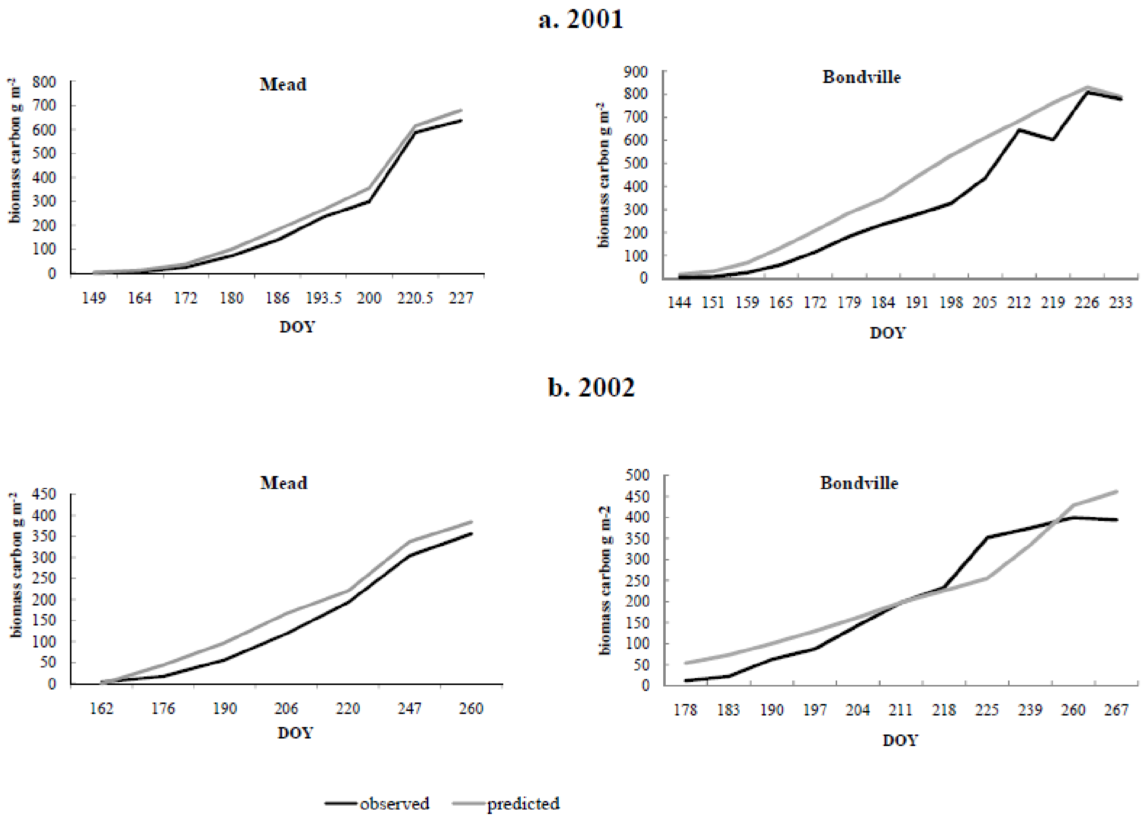


Figure 5. Observed and predicted total aboveground biomass carbon at Mead and Bondville Ameriflux eddy covariance flux tower sites during a corn year (a. 2001) and a soybean year (b. 2002).

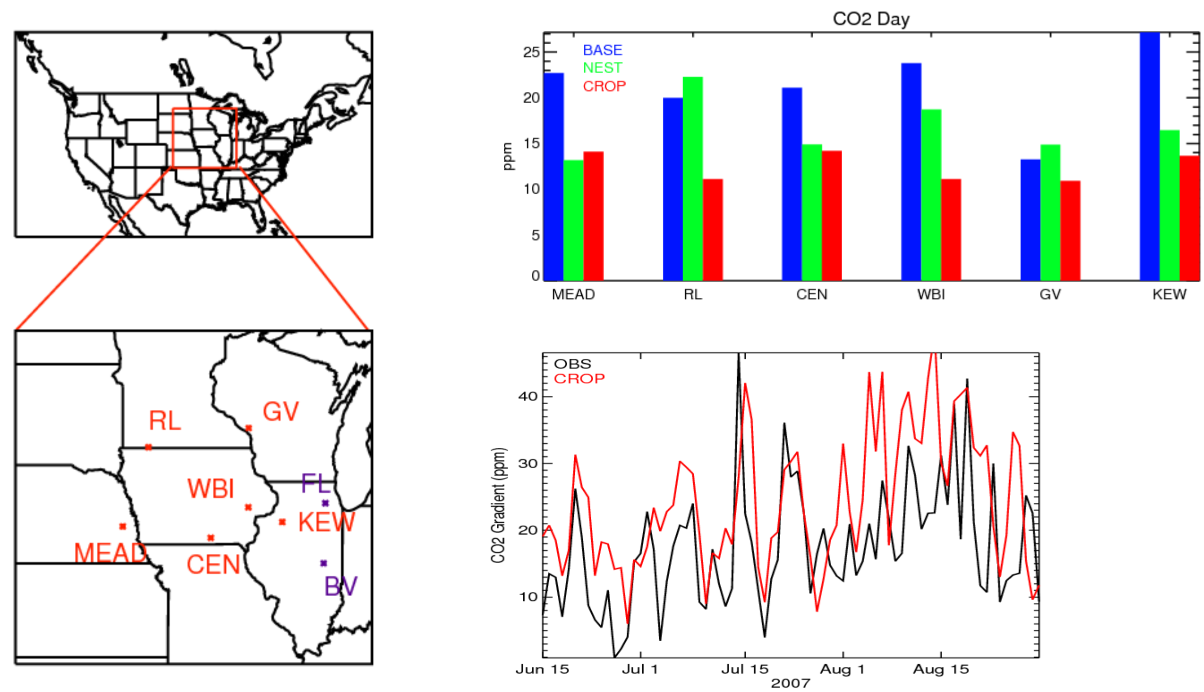


Fig. 6. Coarse (40 km) and nested (10 km) grids (encompassing the Ring 2 towers region) for coupled SiBcrop-RAMS simulations of atmospheric CO2 in summer of 2007 (left), Root-mean square error of CO2 mixing ratio (ppm) simulated by the coupled SiBcrop-RAMS model at each Ring2 tower plus the Centerville tower operated by NOAA (top right; BASE - unmodified model, NEST- 10-km nested grid with original SiB, CROP –with SiBcrop), and Maximum daytime difference in CO2 at 120 m above ground level for each day during summer 2007, as observed by the Ring2 towers and as simulated by SiBcrop-RAMS (bottom right)

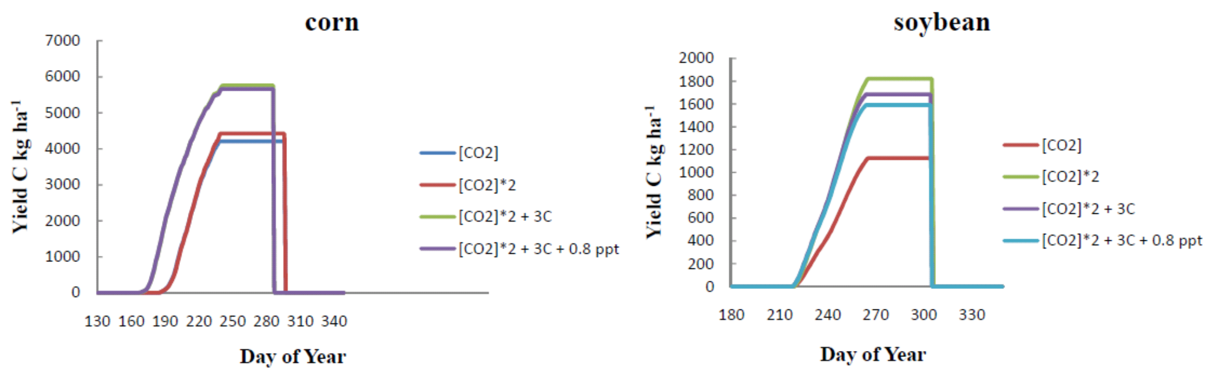


Figure 7. Change in crop yield biomass carbon during the growing season (preliminary results) simulated for Mead rain fed site under several potential future climate scenarios. [CO2]- ambient CO_2 concentration; [CO2]*2- doubled CO_2; [CO2]*2 + 3C- doubled CO_2 and potential temperature rise of 3^0C; [CO2]*2 + 3C + 0.8 ppt- doubled CO_2, temperature rise of 3^0C, and 20 percent reduction of precipitation

Final Report (September, 2006 – September, 2009

Evaluating effects of climate changes on Midwest agroecosystems using a climate-crop coupled model

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1) ABSTRACT

The overall goal is to understand and quantify how critical ecosystem structure, functioning, and climate feedbacks in major terrestrial ecosystems of the Midwest will change at the regional scale under climate change. Multiple analyses combined with modeling were used to achieve this goal. During the project's three years, we analyzed the historical climate and model projected scenario climates were analyzed to diagnose regional climate change in the Midwestern region. We used the coupled climate/crop model system to project future trends of soil carbon in the region. Main results include: 1) the U.S. Midwest had experienced summer daytime cooling during past decades while global warming was evident; 2) soil organic carbon (SOC) would decrease under the future climate scenarios over this intensive agricultural region; and 3) any uncertainty in absolute SOC would translate directly into its trend, unlike other variables such as temperature whose trends are independent of their values themselves, contrasting the reliability of SOC trend with temperature change.

2) RESEARCH ACTIVITIES

The research activities throughout the project period are broadly grouped into four categories: model and tool development, Midwestern climate response to global climate change**,** soil organic carbon trends in the Midwest, and other climate change related activities.

a) Model and tool development

This group of activities was aimed at task (1) of the proposal: Refine model parameterizations to take advantage of recent advances and field observations of key ecosystem functioning in a corn-soybean dominated agroecosystem.

i) *Optimizing photosynthesis parameters in the coupled model.* Photosynthetic parameters have major impacts on the outcome results in the proposed study. Unfortunately, in the existing models they are determined crudely, often assuming uniform constants across species. By applying a global optimization algorithm, a shuffled complex evolution method [SCE-UA, Duan et al., 1992], we optimized several photosynthetic and microbial respiration parameters for corn and soybean in LSM by minimizing model errors in simulating CO_2 fluxes from AmeriFlux at Bondville, IL during the 1999 and 2000 growing seasons. As anticipated, the SCE-UA algorithm improved the model performances for corn and soybean at the local scale. Improvements for corn are not as obvious as those for soybean, because the original parameters performed better for corn than soybean. After calibrations, sensitive parameters have been identified. These parameters with specific values for corn and soybean, which are individually distinguished from the original values, control the simulated net CO_2 fluxes. And these parameters need emphasis on further research. As a consequence of the calibrations, an updated coupled model incorporating new values of calibrated parameters and a revised flux-integration treatment is established. This new model works better for small scales than the default one and brings more information to the large-scale aspect of the system. The results are reported in Xue and Pan [2008].

ii) *Canopy turbulence modeling*. Atmospheric turbulence exerts strong impacts on H_2O and CO_2 transport from near the ground though the canopy top into the free atmosphere. Soil and growth transpiration is likely affected by complex turbulence inside the canopy. In analogy to plant spore transport, we have developed a quasi-statistical model that can be eventually used to estimate respiration CO_2 fluxes through the crop canopy. As the first step, the model is being validated with available pathogen spore transports [Andrade, 2009].

iii) *Coupled crop modeling.* A regional atmospheric model [MM5, Grell et al., 1993] coupled with a land surface model [LSM1&LSM2, Bonan et al., 2006] and crop models [CERES/SOYGROW, Jones et al., 2003] were used. The model skill was evaluated by relevant comparisons against observed data. Sensitivity simulations were carried out to explore the impact of change in agricultural practices (e.g. change in row density, utilization of fertilizers) as well background atmospheric CO_2 concentration on CO_2 and water vapor fluxes at the surface. Changes in the agricultural practices were considered in the corn and soybean areas of the Midwest.

iv) *Assessment of regional climate model skill and impact of model resolution.* We evaluate the skill of an ensemble of global models and an ensemble of regional models to simulate climate and hydrological variables of importance to the carbon cycle and agroecosystems in the Midwest [Takle et al., 2009]. Regional climate models, having higher spatial resolution than global models, can be expected to produce spatial refinement (over global model results) of climate details in regions of high topographic variability (e.g., mountains, coastal areas, large inland water bodies) or in regions of known large climate gradients (e.g., Sahel). But do they improve on global model results in regions where such variability is low? The Upper Mississippi River Basin (UMRB), a region of relatively low topographic and climate variability, is a suitable region to explore this question. We use daily output of GCM and RCM precipitation and temperature to compute monthly and basin-average precipitation and temperature (Figure 1) and as input to SWAT to calculate streamflow (bottom graphs in Fig. 1) for the period 1981-2003. RCMs have a sharper spring peak in precipitation than GCMs and observations, and both sets have their ensemble means occurring a month too early. Oddly, all RCMs simulate an erroneous secondary maximum in November. Both sets have too much precipitation for December through May and too little from June through November, with RCM departures from observed being greater than those for GCMs. RCMs tend to have more of a warm bias, while GCMs tend to have a cold bias of smaller magnitude. Both sets of models have excessive amplitude of the seasonal cycle of streamflow as might be expected from the monthly precipitation results, with first half of the year being too high and second half too low. Observations have a broad peak from April through June with peak maximum value in April, whereas RCMs give a similar timing of a broad peak but with maximum in May. The ensemble mean of the GCM-driven simulations by SWAT captures both the timing and amplitude of the seasonal cycle.

Despite the wide range in annual mean streamflow simulated by the individual global and regional models, both of the respective ensembles have means quite close to the observed mean and the major characteristics of the seasonal variation. The results suggest that at the basin scale for this basin having very little topographic forcing, the ensemble of the GCMs exhibits higher skill in simulating the climate and streamflow than the RCMs although both sets represent essential climate and hydrologic characteristics quite well. The time series of annual streamflow as simulated by SWAT with RCM input (Fig. 2) reveals that each model tends to have a bias that is constant in sign and in its proportion to magnitude of the streamflow: a model that is biased high is high in almost every year by about the same fraction of the observed for that year. The RCMs provide conditions leading to a wide range of streamflow, although most RCMs capture the extreme low flow of 1988 and the very high flow in 1993.

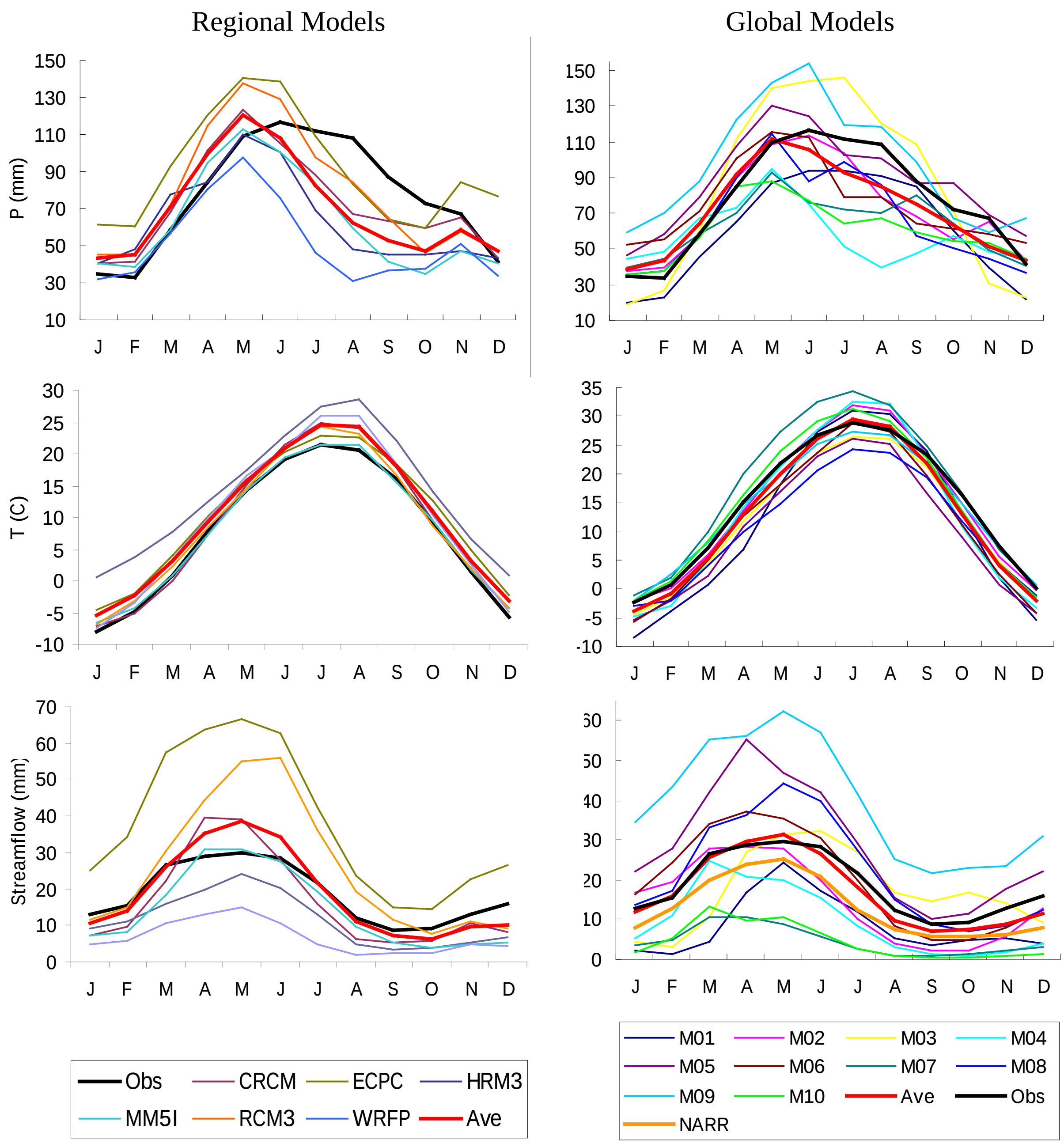

FIG. 1. The domain (UMRB) and period (multiple years) averaged monthly means of the daily temperature (mean for RCMs and maximum for GCMs), precipitation, and the SWAT-simulated Streamflow. See Lu et al. (2009) for more description.

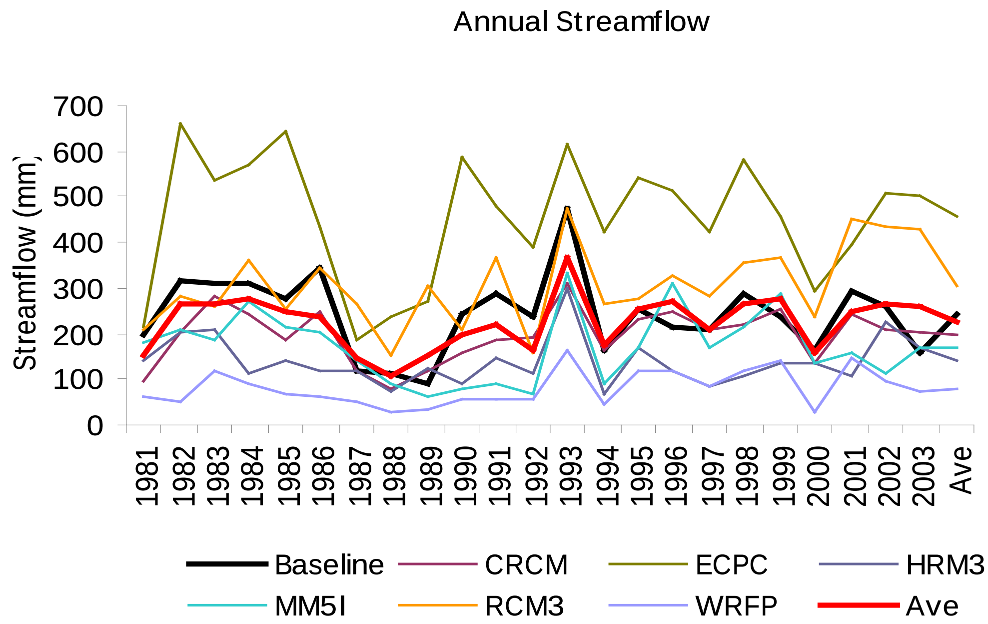

Fig. 2. Interannual streamflows as simulated by SWAT and driven by RCMs.

b) Midwestern climate response to global climate change

This group of activities was to address our proposed tasks 2 and 3: Task 2: Assess climate change impacts on the Midwest agroecosystem functioning and structure based on dynamically downscaled regional climate scenarios that include atmosphere-crop feedbacks Task 3: Quantify individual and synergetic effects of climate change factors on the ecosystem function and structure.

1) IPCC AR4 scenario climates in the Midwest region. Temperature and precipitation are major factors regulating the magnitude of biologically mediated surface exchanges of carbon. Consequently, climate change would alter CO_2 fluxes between the atmosphere and soil carbon pools. The B1, A1b, and A2 scenario climates from three GCMs (French, Canadian, and German) representing respectively cold/wet, normal, and warm/dry models were selected and analyzed for three time windows: 1961-2000, 2046-2065, and 2081-2100 [IPCC, 2007] (Fig. 3). Despite differences among the models, all three GCMs project growing-season (May-September) warming of 1.6-1.8^{o}C in the Midwest by the mid-21st century under the least aggressive B1 scenario. The regionally diverse A2 scenario produces an additional 1^{o}C warming over the B1 scenario, while the balanced A1b scenario predicts a climate that is about 0.2^{o}C cooler than the A2 scenario. Future precipitation amounts during the growing season are predicted to increase by 10-30% depending on the model and scenario [Pan et al., 2009a].

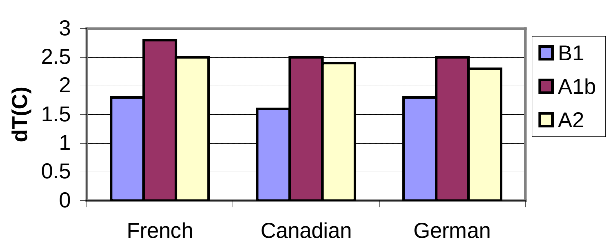

Fig. 3. Projected growing-season warming at Ames, IA by three IPCC AOGCM for Mid-21st (2046-2065) century as compared the past (1961-2000).

ii) Abnormal summer cooling in the Midwest. Figure 4 shows the linear trends of summer mean daily maximum surface temperature (hereinafter Tmax) during the different periods [Pan et al., 2009b]. During the entire 20th century, the south-central U.S. cooled 0.5-2.0 °C, while most parts of the U.S. slightly warmed. During the 50 years (1951-2000), the south-central U.S. cooling was more extensive with most parts being cooled by 1.0-1.5 °C (Fig. 4a). The most extensive and strongest cooling occurred in the 1951-75 period when the cooling spread over all the south-eastern states including TX (Fig. 4b). A strip of 3°C cooling ran from SC to eastern TX. During the last 25 years (1976-2000), the peak global warming period, the cooling was shifted to the central section of the U.S. with the largest cooling of over 2.0°C located at the IA-NE-SD border (Fig. 4c). This well-defined region of cooling oriented in the NW-SE direction, in contrast with NE-SW direction in the 50-yr period (Fig. 4b). While central-eastern U.S. cooling is evident for most parts of the 20th century, the cooling magnitude and location differ for different periods. The overall cooling within the 50-yr periods consists of two distinct periods and locations: the north-central U.S. cooling in the 1976-2000 period, hereafter referred to as north-central cooling center (NCC) and south-central cooling in 1951-1975 period, hereafter referred to as south-central cooling center (SCC). The time series of Tmax in NCC and SCC as indicated by the dark rectangles in Figs. 4b and 4c show that cooling in NCC was mainly concentrated in the 1986-1996 period, while the southern cooling in SCC was persistent between 1954-1967 (Fig. 4d).

iii) Observed 20th century climate in the Midwest. Although during the 20th century the global surface temperature warmed by 0.6°C, some regions of the world have actually cooled, especially for summer daytime maximum temperatures. Previously, we identified four major "warming holes", most noticeably in the eastern and central U.S., which likely impact Midwest agroecosystems. To further diagnose the underlying causes, we analyzed the average flow patterns and found that an increased prevalence of cold air advection regimes characterized by northerly wind flow has been largely responsible for lack of warming in the central US [Pan, et al., 2009b]. Further analysis of the 850 mb wind pattern during the last

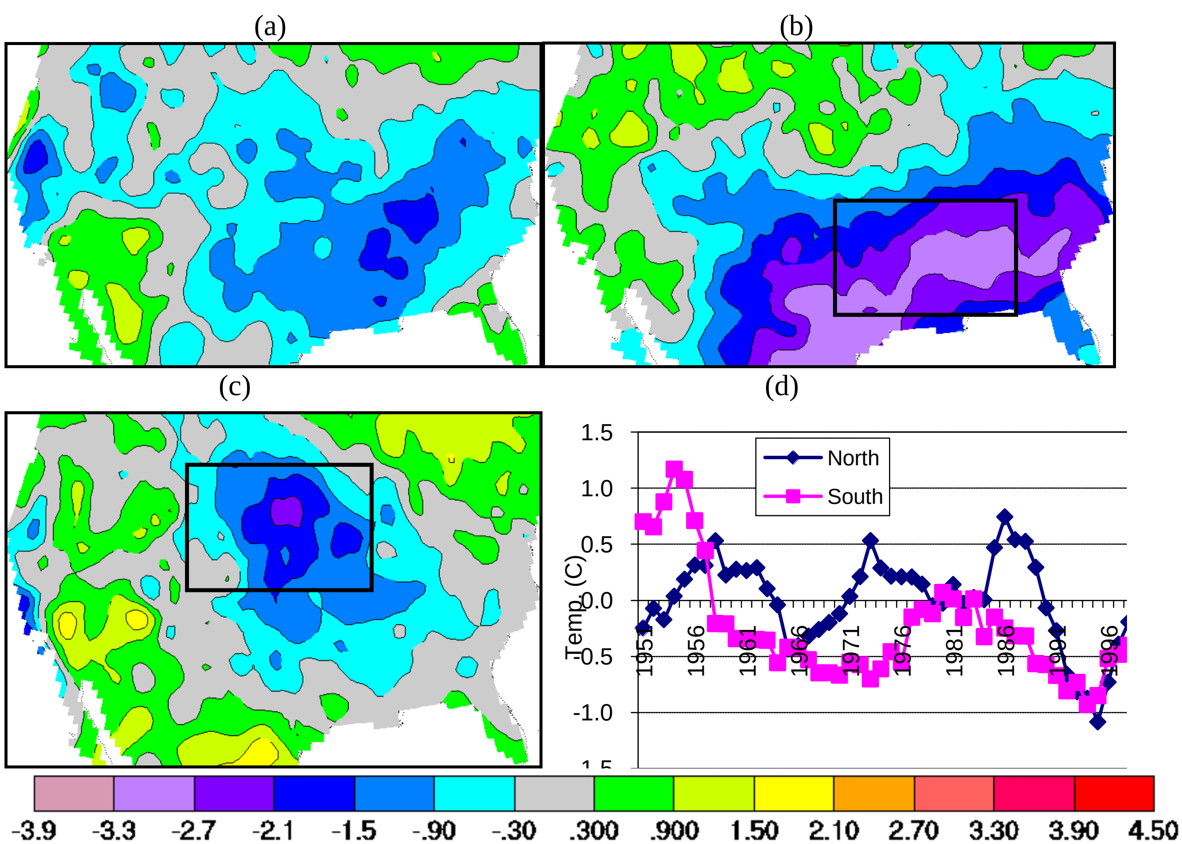

Fig. 4. Summer mean daily maximum surface temperature (Tmax) trends (°C) during various periods of the 20th century. (a): 1951-2000; (b): 1951-1975; and (c): 1976-2000. (d) Time series of Tmax in the north-central (40-50N by 105-90W) and south-central U.S. (30-40N by 100-85W), as delineated by the rectangles in (b) and (c).

50 years indicates that the increase in northerly wind flow is being forced by a NW-SE pressure gradient enhanced by excessive warming over the western mountains (Fig. 5). Further amplification of the western ridge associated with global warming may further increase the frequency of northerly flow, which is likely to slow the warming or even cool the central and north-central U.S. during summer.

vi) Global "warming holes". While searching for reasons why the abnormal cooling, termed "warming hole" (WH), occurs in the central U.S., we identified three other WHs in south-central China, south-central South America, and northern Australia. All the WHs (except for the Australian one) occur in the general eastern slopes of major mountain ranges where low-level jets are prominent. A tentative global WH formation mechanism follows: i) Increased moisture convergence due to increased atmospheric water vapor and/or increased LLJ strength or frequency enhances cloudiness and precipitation. ii) Increased cloudiness attenuates solar radiation and surface heating during daytime (Tmax). iii) Deep soil planted with intensive crops (except AuWH) provides soil water storage and transpiration, and thus suppresses afternoon heating in summer. Other factors contributing to the cooling in the WHs likely include changes in agricultural practices that lead to increased plant transpiration, reduced daytime warming, and the increased frequency of El Niño events that increased precipitation over the USWH and SAWH. Atmospheric aerosols are believed to partly contribute to the cooling associated with the China WH.

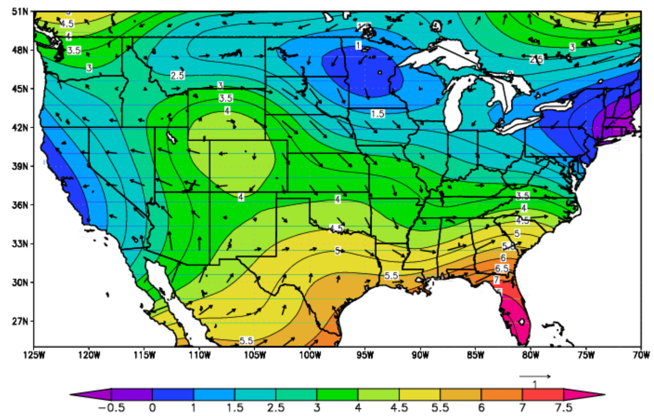

Fig. 5. Difference in 850 mb wind and 700 mb geopotential height between 1976-2000 and 1951-1975 periods in summer, showing cold-air advection that might contribute to the summer cooling in the Midwest region (Pan et al., 2009b).

c) Soil organic carbon trends in Midwest

i) Soil carbon trend in the 21st century projected by DayCENT (Parton et at., 1987). We used DayCENT, the CENTURY model with a daily rather than a monthly time step, driven by past climate and IPCC AR4 scenario climates to project trends of soil organic carbon (SOC) pools for the Midwest cropland under various management strategies. Under all scenario climates, DayCENT simulations produce a 3-26% decline in SOC by mid-century if current management options (conservation tillage, soybean-corn rotation, and moderate fertilizer application) continue (Fig. 6). The SOC differences among the scenarios are within 8% of each other, smaller than the inter-model difference of 23%, suggesting that the uncertainty in SOC levels is largely attributable to individual GCM differences. Further diagnoses indicated that the SOC decline is more (less) due to heterotrophic soil respiration (NPP), suggesting dominance of warming effects on soil microbial decomposition.

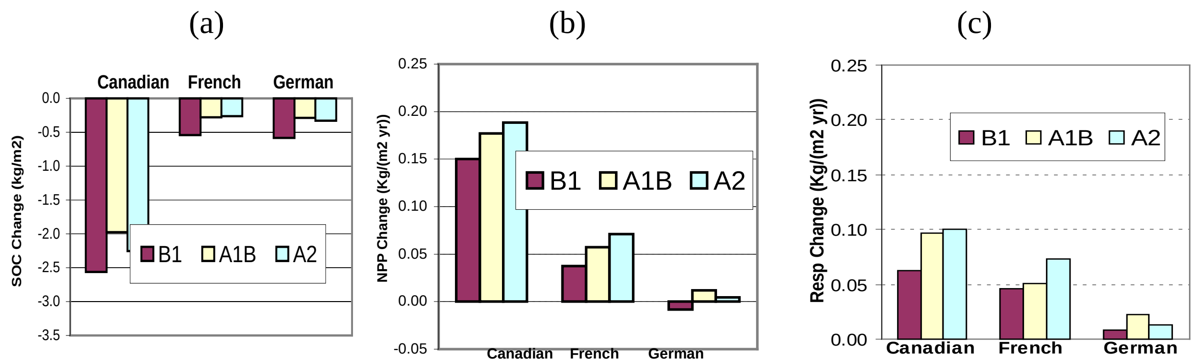

Fig. 6. DayCENT simulated changes in SOC, NPP, and respiration changes from 1961-2000 to 2046-2065. (a): SOC, (b): NPP, (c): respiration.

ii) Tillage effects on SOC. The observed climate with control management (defined as corn-soybean rotation, conservational tillage, and moderate nitrogen fertilizer) maintains a roughly steady SOC level. The model simulated a gradual decrease in SOC in the top 20 cm soil layer from 8 kg m^{-2} in 1894 to about 4 kg m^{-2} in early 1960s (Fig. 6a), in close agreement with previous studies (e.g., Smith 1999). After that, SOC started to recover due to nitrogen fertilization, started in 1951, and the adoption of conservation tillage, started in the 1960's. At the end of the 20^{th} century, the soil carbon recovered up to around 6 kg m^{-2}. The details of results (i) and (ii) are reported in Pan et al., [2009a].

d) Other climate change related activities

i) Impacts of wind power farms on the Midwest agroecosystem. In recent decades there has been an increase in the use of wind farms within intensely managed cropland across the Midwest. In the future, it is possible that the aerial coverage of wind farms will expand dramatically. Recent studies suggest that wind farms have an impact on surface meteorological conditions, such as temperature, specific humidity, and surface thermal fluxes, by altering the flow and turbulence characteristics of the boundary-layer [Adams and Keith, 2007]. Resulting changes in the regional average maximum and minimum temperatures can approach +/-1^{o}C. A preliminary sensitivity analysis of this potential regional effect on crops and hence SOC was implemented by linearly perturbing daily maximum and minimum temperatures in a manner consistent with the inferred impact of large wind farms. These perturbations produced mild linear perturbations in the soil carbon pools and carbon fluxes (figures not shown). Relatively simple modifications are presently added in our regional model in order to incorporate the impact of wind farms on the near-surface climate.

ii) *Investigation of Chaos in simplified Climate Systems.* Most advances in climate change science have involved the continual development of models of ever increasing complexity with the hope that such models will better capture the complete set of dynamics existing in the real climate system. The assumption is that greater complexity will, if carefully implemented, result in better model predictability. Held [2007] was critical of this approach because it has rendered any thorough understanding of the model dynamics impossible. Hogg and Blundell [2006] found that in various simplified dynamical models of the atmosphere and ocean, weather variability can produce low-frequency variability in the ocean which then is able to imprint itself onto the atmosphere on long time scale. This suggests that the true climate system may exhibit chaotic sensitivity to both initial conditions and external forcing. This would suggest that meaningful predictions of the future climate by GCMs may require an ensemble of runs and that the validity of any single realization has limited predictability as do single forecasts produced by NWP models. In parallel to modeling studies, we also investigate the potential existence of this chaotic climate behavior in a simplified 4-layer quasi-geostrophic model coupled ocean-atmosphere model. Using a well-established closure known as the Direct Interaction Approximation, we allow the model to generate ensemble statistics directly rather than individual realizations of the climate. Our hope is to investigate the sensitivity of these statistics to perturbations in initial weather conditions and to obtain an initial understanding of the mechanisms through which chaos in the climate system can be introduced. These results would add a great deal of insight into how phenomena such as El Nino, the Madden Julian Oscillation, and various others might interact with the climate system.

3) RESEARCH HIGHLIGHTS

- The inter-model difference in the projected 21st century climate under a given GHG emission scenario is larger than the variations between different scenarios, indicating that most uncertainty lies in the choice of GCM.

- The net CO_2 flux, the residual between the large NPP and CO_2 respiration, oscillates over the U.S. Midwest, but when averaged over long time periods, it is very close to zero. The sign of the long-term averaged net CO_2 flux is sensitive to weather conditions during the period.

- Any uncertainty in absolute SOC would translate directly into its trend, unlike other variables such as temperature whose trends are independent of their values themselves, contrasting the reliability of SOC trend with temperature change.

- For the mid-continent climate of the US Midwest where terrain forcing in minimal, an ensemble of global climate models performs slightly better than an ensemble of regional climate models in simulating basin-average climate and streamflow over a fairly large basin (Upper Mississippi River Basin)

- The central U.S. has experienced summer cooling in the past three decades despite an increase in global mean temperature [Pan et al, 2004]. This cooling area along with the broader cooling in eastern U.S. during the 20th century is the most extensive lack-of-warming (cooling) in the world. Past studies seeking the underlying causes for the abnormality indicated that local land surface changes including agricultural evolution [Kalnay and Cai, 2003] and increased moisture transport from the Gulf of Mexico [Robinson et al, 2002] might be responsible for the cooling. Here we propose another mechanism: It is well documented that the western mountain regions have significantly warmed more than the central and eastern U.S. This warming forms the ridging in the western U.S. The ridging induces the northerly winds that advect colder air from the north and thus contributes to the Midwest cooling.

- Three other WHs similar to the one in the central U.S. one are identified in south-central China, south-central South America, and northern Australia. All the WHs (except for the Australian one) occur in the general eastern slopes of major mountain ranges where low-level jets are prominent. A tentative global WH formation mechanism follows: i) Increased moisture convergence due to increased atmospheric water vapor and/or increased LLJ strength or frequency enhances cloudiness and precipitation. ii) Increased cloudiness attenuates solar radiation and surface heating during daytime (Tmax). iii) Deep soil planted with intensive crops (except AuWH) provides soil water storage and transpiration, and thus suppresses afternoon heating in summer.

4) RESEARCH PRODUCTS

- A computer model of simplified quasi-geostrophic 4-layer climate system for studying chaos.
- A soil carbon and CO_2 budget data set for current and future climates
- Model-generated trends in surface winds between 1979-2004.
- A set of modeling tools for merging global and regional climate model output into ecosystem models such as the CENTURY model
- Twelve peer-reviewed journal papers/book chapters. Two thesis/dissertations and a number of conference abstracts/presentations.

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6) STUDENTS DEGREES SUPPORTED

The following students received partial financial support from this grant during various stages of the their programs.

- **David Andrade, Master's, May, 2007. Dept. of Earth and Atmospheric Sciences, St. Louis University.**
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- **David Andrade, Ph.D. May, 2010 (expected). Dept. of Earth and Atmospheric Sciences, St. Louis University.**
- **Nichole McKinney, BS in meteorology, Dept. of Earth and Atmospheric Sciences, St. Louis University.**
- **Lulin Xue, Ph. D in meteorology, Dept. of Earth and Atmospheric Sciences, St. Louis University.**

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Final Report
Midwestern Regional Center of the Department of Energy's National Institute for Climatic Change Research

Project Title:
Collaborative Research: Interactive Effects of Altered Rainfall Timing and Elevated Temperature on Soil Communities and Processes

Principal Investigator:
John M. Blair
Kansas State University, Manhattan, KS

Co-Investigator(s):
Alan K. Knapp
Matthew D. Wallenstein
Colorado State University, Fort Collins, CO

1. Abstract.
Temperature and rainfall are critical drivers of ecological processes in grasslands. In the Central Plains mean temperatures are expected to increase and rainfall patterns are predicted to become more variable and extreme. We assessed the potential consequences of these changes with field-scale rainfall manipulation shelters that allowed us to alter the timing of growing season rainfall and increase temperature over intact grassland. Changes in the timing of rainfall events (larger events with longer inter-rainfall droughts), without a change in total precipitation amount, altered soil moisture dynamics, with long-term consequences for soil, plant, community and ecosystem processes. We found significant reductions in both plant productivity and soil respiration with more extreme rainfall patterns, and increased potential for N losses. Warming exacerbated the negative effects of altered rainfall timing on plant productivity and soil respiration, presumably due to increased water limitations with elevated temperature. Understanding the interactive effects of more extreme rainfall patterns and warmer temperatures will be critical for predicting the sustainability of grassland resources and ecosystem services under a future climate.

2. Research activities
Our objectives were (1) to determine how above- and belowground ecosystem processes respond to increases in ambient temperature and more extreme patterns of precipitation, and (2) to identify the potential consequences of these responses for grassland ecosystem function under an altered climate. To address these objectives, we expanded and continued a long-term field experiment in which the timing of rainfall events and temperature are simultaneously manipulated in native grassland. Our central hypothesis was that changes in the timing of rainfall events, as predicted by GCMs, and increases in mean temperature will significantly alter temporal patterns and depth distributions of soil moisture and, consequently, key above- and belowground processes, including plant productivity, soil respiration, soil nutrient availability and root dynamics. Understanding these responses will be critical for explaining and predicting changes in the structure and functioning of grassland ecosystems under a more variable future climate. Specific objectives included:

- determining how altered patterns of growing season precipitation and increased temperatures affect aboveground plant productivity (ANPP).
- quantifying how key soil processes, including soil CO_2 flux and nitrogen transformations (N availability and potential for loss), respond to altered patterns of growing season precipitation and increased temperature.
- determining how altered patterns of growing season precipitation and increased temperatures affect belowground plant processes, including allocation to root biomass, root tissue chemistry and the turnover of fine roots.
- evaluating the ecosystem-level consequences (i.e., soil organic matter storage and turnover, nutrient cycling processes, primary productivity) of soil and plant responses to altered rainfall and temperature regimes.

To address these objectives, we continued a long-term rainfall manipulation experiment, initiated in 1997, at the Konza Prairie Biological Station (KPBS), a 3487-ha tallgrass prairie, which is a part of the NSF Long-Term Ecological Research network. The tallgrass prairie is a highly productive grassland, of significant agricultural and economic importance to the U.S. It is also particularly appropriate for addressing climate change studies because production responses to climate variability are large (up to 4-fold from dry to wet years), and water availability plays an important role in regulating soil processes and soil communities. Our approach for studying potential impacts of climate change has been to experimentally manipulate rainfall patterns and temperature in native grassland plots under realistic field conditions. We use modified rainout shelters which exclude rainfall from 7.6 x 7.6 m experimental plots and allow us to reapply natural rainfall as dictated by our experimental protocol. These Rainfall Manipulation Plots (RaMPs) allow us to manipulate both the amount and the temporal variability in rainfall reaching the plots. The RaMPs have clear plastic roofs, which divert natural rainfall into two 4000 L reservoirs capable of storing 10 cm of rain. The rain is reapplied using an overhead sprinkler system. In spring 2003, we installed two 4-m^2 temperature manipulation plots in each RaMP (and each non-sheltered reference plot), modifying the experiment to a split-plot design, with precipitation as the whole-plot treatment and warming as the subplot treatment (Fig. 1). Thus, we altered rainfall timing while assessing the impacts of increased temperature, as well as their interactive effects, on this grassland ecosystem. Treatments are currently implemented as follows:

<u>Ambient precipitation regime (Trt. 1)</u>: In six of the RaMPs, rainfall is collected and reapplied to the plots each time a natural rainfall event occurs. Rain gauges outside the RaMPs and an in-line flowmeter allows us to confirm that precipitation amounts applied inside the RaMPs equal the amounts of rain falling outside.

<u>Altered precipitation regime (Trt. 2)</u>: The other six RaMPs are used to impose a predicted future rainfall regime of increased temporal variability in rainfall inputs (Fig. 2) and soil moisture (Fig. 3) relative to ambient precipitation patterns. This is achieved by lengthening the current ambient dry intervals between rainfall events by 50%. For example, a 2 week period between ambient rainfall events would be lengthened to 3 weeks. All rainfall during these experimentally lengthened dry periods is stored and applied as a single larger event at the end of the dry interval.

The total amount of growing season rainfall applied in this treatment is identical to ambient, only the event size and temporal distribution of inputs is altered.

Increased air and soil temperatures with ambient or altered rainfall patterns (Trt. 3&4): Each RaMP contains four 2 x 2 m subplots. Overhead rectangular IR lamps (Kalglo MRM-1215 1500-W model) are suspended ca. 1.5 m above the canopy in two subplots. The lamps simulate climate warming (~2 ^oC) by enhancing downward IR flux (~75 W m^{-2}) to the soil surface/plant canopy and reducing the diurnal range in air temperature. In contrast to rainfall treatments, warming occurs year round. We raise the lamps during the growing season as vegetation height increases to maintain a constant IR flux at the canopy surface, and to avoid unrealistic radiation loads on the canopy. The 4-m^2 plots are of sufficient size to allow us to designate 1-m^2 areas (4/RaMP) for non-destructive plant species composition sampling, as well as areas for ANPP estimates (0.1 m^2 quadrats), and other response variables measured as outlined below. Initial performance of the IR lamps and effects on canopy temperatures and soil moisture indicate that the treatment is effective (Fig. 4).

This NIGEC project focused primarily on belowground responses to changes in rainfall patterns and ambient temperatures. However, to fully evaluate the impact of climate change on grassland ecosystems, these results must be integrated with comparable studies of aboveground processes, including plant ecophysiological responses, changes in aboveground productivity, and shifts in plant species composition. We have been addressing these aboveground responses with additional funding from the USDA and NSF. In Table 1, we summarize the main above- and belowground responses being measured.

Table 1. Summary of response variables, methods and investigator responsibility.

Response	***Method***	***Responsibility***
Soil moisture	TDR/neutron probe	Blair/Res. Asst.
Microclimate	CR-10 data logger/sensors	Knapp/Research Asst.
Grass/forb ecophysiology	LICOR 6400.	Knapp/student
Plant species composition	Canopy coverage	Smith/Collins
Aboveground NPP	Harvest method	Knapp
Grass/forb tissue N	Carlo-Erba C/N analyzer	Blair
Soil CO_2 flux	Field chamber/LICOR	Knapp/Research Asst
Soil OM and N	Soil cores/lab analyses	Blair/student
Root biomass and nutrients	Soil cores	Blair/student
Root litter decomposition	Litterbag	Blair/student
Root distribution & turnover	Minirhizotron	Blair/student
Soil N availability	Resin bags	Blair
Soil microbial activity	lab incubations	Wallenstein
Soil microbial community	MPS/DNA tagging	Jumpponen

3. Research highlights

The rainfall treatments effectively altered natural rainfall patterns over the course of the study, resulting in an “altered” rainfall regime with fewer growing season rainfall events, larger mean rainfall event size, and longer dry intervals between rainfall events, relative to the “ambient” rainfall pattern in a given year. The altered rainfall timing treatment also affected soil moisture dynamics, which is a critical driver of plant responses in these grasslands (Knapp et al. 2008). Specifically, altered rainfall timing resulted in a 14% decrease in mean daily soil water content

(SWC) across years and an 18% increase in the CV of daily SWC, despite receiving the same growing season rainfall quantities as the ambient rainfall timing treatment.

Results to date have identified several critical aboveground and belowground community and ecosystem processes grasslands that are responsive to changes in the timing of rainfall events and/or elevated temperature. For example, altered rainfall timing (longer inter-rainfall droughts interspersed with larger individual precipitation events, with no change in annual rainfall amounts) significantly reduced aboveground net primary productivity by 13-22% (ANPP) in 5 out of 12 years, despite high year-to-year variability in ambient rainfall patterns and mean plant productivity (Fig. 1). Averaged across all years, ANPP was 10% lower in the altered rainfall timing treatment ($P<0.001$).

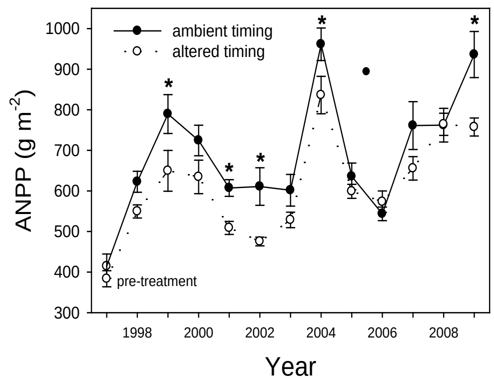

Figure 1. Summary of ANPP responses to rainfall treatments from 1998-2009. Asterisks represent significant differences between treatments.

Soil CO_2 flux is a valuable integrative measure of microbial processes and plant activities below ground. Soil CO_2 flux was affected by altered rainfall timing, with rainfall timing x date interactions in all years, and significant main effects of the rainfall treatments in dry years. When significant main effects occurred, it was due to reductions in mean annual soil CO_2 flux under altered rainfall timing (Fig. 2). As with ANPP, soil CO_2 flux was positively correlated with mean seasonal soil water content and negatively correlated with indices of soil moisture variability. This important finding suggests that increases in the temporal variability in soil water content resulting from climate change will significantly alter key C cycling processes in grassland ecosystems. We expect continued reductions in both ANPP and soil CO_2 flux with more variable rainfall regimes, and we predict that increased temperatures will exacerbate variability in surface soil water content and further alter C cycling, leading to changes in soil C and N pools. We are continuing our climate manipulations to assess the longer-term responses to altered rainfall and temperature regimes, as well as potential changes in specific soil C and N pools.

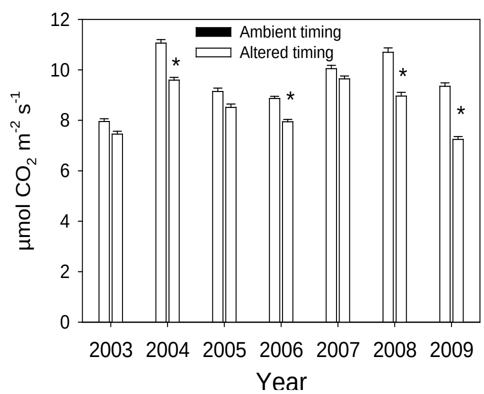

Figure 2. Summary of mean growing season soil CO_2 flux responses to rainfall treatments from 2003-2009. Asterisks represent significant differences between rainfall treatments.

The experimental heating treatment is allowing us to evaluate the interactive effects of altered rainfall timing and increased temperatures on ecosystem processes, including both ANPP and soil CO_2 flux. Results-to-date indicate that warming can reduce both ANPP and soil CO_2 flux in grasslands. Effects of warming on ANPP have been variable, but when significant effects of warming occurred, it resulted in reduced ANPP (mean reduction of

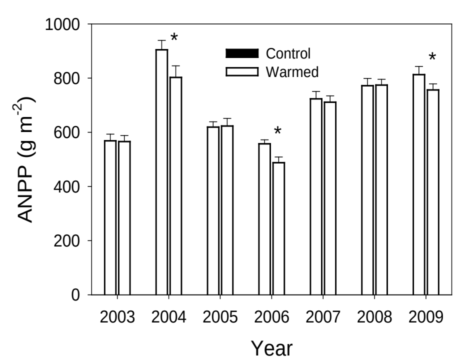

Figure 3. Mean annual ANPP responses to warming treatments from 2003-2009. Asterisks represent significant differences.

10%; Fig. 3). We also found that warming reduced soil CO_2 flux by ~9% in years with lower than average rainfall. In addition, the lowest soil CO_2 flux occurred when warming was combined with altered rainfall timing. In contrast, warming increased soil CO_2 flux in a wetter than average year. Together, these findings suggest that the main effects of warming on soil CO_2 flux in grasslands are mediated by changes in soil water availability (greater water stress with higher temperatures), which indicates that the effects of warming in grasslands may be very different than the typical increase in soil respiration with increasing temperatures observed in more mesic ecosystems (e.g., deciduous forests).

Climate change may also alter soil N mineralization, and we continued to assess potential changes in N availability in response to the rainfall timing and warming treatments. We predict that altered rainfall patterns and increased temperatures will affect patterns and rates of N mineralization, with brief periods of high N availability limited to when dry soils are rewetted. To date, we have found that altered rainfall timing increased resin-collected NO_3-N by an average of 100%, while we have not detected responses to warming. We also collected soil samples that will be used in laboratory incubations to assess long-term changes in mineralizable and C and N pools.

Plant responses to date suggest differential responses of plant functional groups, and in some cases individual plant species, to changes in rainfall timing and warming. Total and C_4 grass biomass has declined and plant species diversity has increased in response to more variable rainfall patterns. Our warming treatments have been imposed for a much shorter period of time than our rainfall manipulations, and we expect that the interactions between warming and precipitation alterations will become more pronounced over time. Nonetheless, several intriguing main effects of warming have already been noted. Warmed plots always have reduced soil moisture relative to ambient temperature plots and plants are typically more water stressed under the elevated temperature treatments. Further, we have noted several strong species specific responses in the two dominant grasses to warming, and we continue to assess longer-term changes in plant community composition.

Fay et al. (2011) summarized the relative impacts of inter- vs. interannual rainfall variability and effects of elevated temperature using 10-years of data from the RaMPs experiment. During this 10-year window, total growing season rainfall varied 2-fold, and we found 50–200% interannual variability in plant growth and aboveground net primary productivity (ANPP), leaf carbon assimilation (ACO_2), and soil CO_2 efflux (JCO_2) despite only 40% variation in mean volumetric soil water content (0–15 cm). Interannual variation in soil moisture was thus amplified in most measures of ecosystem response. Differences between years explained the greatest portion (14–52 %) of the variation in these processes. Experimentally increased intra-annual season rainfall variability doubled the amplitude of intra-annual soil moisture variation and reduced by 15 %, causing most ecosystem processes to decrease 8–40%in some or all years with increased rainfall variability compared to ambient rainfall timing, suggesting reduced ecosystem rainfall use efficiency. Warming treatments increased soil temperature at 5 cm depth, particularly during spring, fall, and winter. Warming advanced canopy green up in spring, increased winter JCO_2 , and reduced summer JCO_2 and forb ANPP, suggesting that the effects of warming differed in cooler versus warmer parts of the year. We conclude that (1) major ecosystem processes in this grassland may be substantially altered by predicted changes in interannual climate variability, intra-annual rainfall variability, and temperature, (2) interannual climate variation was a larger source of variation in ecosystem function than intra-annual rainfall variability and warming, and (3) effects of increased growing season rainfall variability and warming were small, but ecologically important. The relative effects of these climate drivers are likely to vary for different ecosystem processes and in wetter or drier ecosystems.

Historical conditions can affect contemporary microbial responses to environmental factors through the persistence of abiotic changes or through the selection of a more tolerant microbial community. Evans and Wallenstein (2011) used soil samples from the RaMPs project to assess how a history of intensified rainfall would alter microbial functional response to drying and rewetting events, whether this historical legacy was mediated through altered microbial community composition, and how long community and functional legacies persisted under similar conditions. Using soils from the long-term RaMPs rainfall treatments, they measured respiration, microbial biomass, fungal:bacterial ratios and bacterial community composition after collecting soils from the field experiment, and after subjecting them to a series of additional drying–rewetting pulses in the lab. Although rainfall history affected respiration and microbial biomass, the differences between field treatments did not persist throughout our 115-day drying–rewetting incubation. However, soils accustomed to more extreme rainfall did change less in response to lab moisture pulses. In contrast, bacterial community composition did not differ between rainfall manipulation treatments, but became more dissimilar in response to drying–rewetting pulses depending on their previous field conditions. These results suggest that environmental history can affect contemporary rates of biogeochemical processes both through changes in abiotic drivers and through changes in microbial community structure.

Additional analyses of data from the 2010 and 2011 seasons are underway, and we anticipate several additional papers from the core RaMPs project, as well as from recent and ongoing collaborative studies with other groups. Finally, we will continue to make the data from this project available to other groups, through the current project web site, and through linkages to the Konza Prairie LTER database.

4. Research products

A web page (http://www.konza.ksu.edu/ramps/) was established to facilitate dissemination of information about the experimental approach being used (i.e., RaMP design and operation) and project results-to-date.

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Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resiliance to climate change

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Merritt M. Turetsky, Department of Integrative Biology, University of Guelph,

1. Abstract (150 words) - Our research framework addresses several fundamental questions regarding the interactive effects of warming and water manipulations on peatland carbon cycling and how they are modified by peat chemistry and vegetation changes. We choose six sites in Seney National Wildlife Refuge that represent a gradient of long-term water manipulations, plus we picked one site at another peatland to conduct our short-term warming experiment. We installed our warming treatments in the fall of 2008/spring 2008. We measured hydrologic changes, carbon (DOC, CO_2 and CH_4) fluxes, plant community dynamics and production, decomposition and collected peat cores for microbial analysis. We expanded the scope of our original project by bringing on two colleagues, Tom Pypker (MTU, received an internal grant to add eddy flux towers to our study) Mike Waddington (U. of Hamilton), who added an in-depth water cycling component to the project and Evan Kane (USFS) to conduct DOC studies.

2. Research Activities - Our overall goal is to implement a field experiment designed to tease apart the interactive effects of warming and water manipulations on peatland carbon cycling and how they are modified by peat chemistry and vegetation changes. Our original designed called for using warming lamps in areas of Seney National Wildlife Refuge (SNWR) that have been under long-term drainage and short-term drainage, and in areas with no drainage. Due to logistical constraints, we had to modify our experimental design and use open top chambers (OTC's). However, we initiated a new short-term warming experiment to test how OTC's compare to warming lamps at a new site, Pequaming, which has an onsite power source. We further expanded the scope of our project by bringing on three colleagues, Tom Pypker (MTU, received an internal grant to add eddy flux towers to our site), Mike Waddington (U. of Hamilton), who are adding an eddy flux and in depth water cycling component to the project. We have also developed collaboration with Evan Kane (USFS) to conduct DOC studies and Andrew Burton et al. who received a NICCR grant entitled "Short and long-term acclimation of root respiration in woody plants and the moderation of warming-induced enhancement of soil CO_2 effux" who used our warming plots to measure root respiration.

We have done the following.

1. **Picked study sites in Seney and Pequaming**. The Pequaming site is being used as the site for our short-term warming experiments, while SNWR is being used for our long-term drainage studies. We picked seven sites in SNWR that represents a gradient of long-term water manipulations (Figs. 1 & 2) and a control site that has had no water manipulations (site not shown). We also picked one site at another peatland near Pequaming to conduct our short-term warming (Fig. 2).

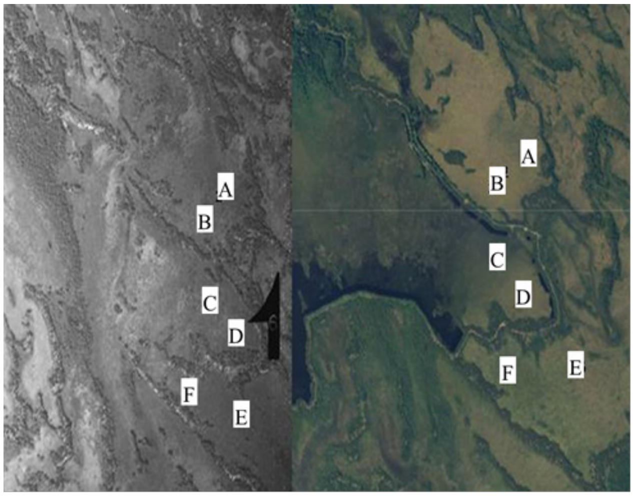


Figure 1. Locations of SNWR study sites in 1939 (left) and 2002 (right). Notice the construction of the road in the early 1950's that dewatered sites E & F, added extra water to site C & D and mostly left sites A & B unimpacted.

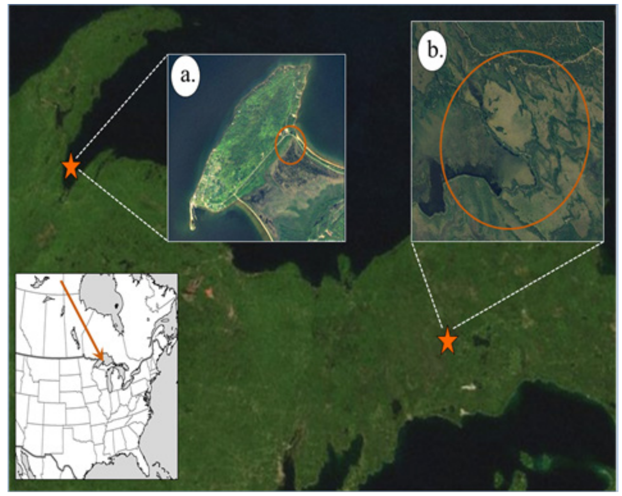


Figure 2. Short-term warming site at a) Pequaming and long term drainage site in b) Seney National Wildlife Refuge.

2. **Installed boardwalks**. We installed boardwalks at all study sites to minimize damage to our sites.
3. **Built all flux chambers and collars**. We built over 50 collars and installed them.
4. **Installed environmental monitoring equipment at each site**. We are continuously measuring water levels, soil temperature and water content using a combination of ibuttons, pressure transducers, thermocouples and dataloggers.
5. **Conducted initial floristics**. Currently conducting baseline vegetation monitoring.
6. **Installed eddy flux towers**. Seasonal changes in site-level CH_4, CO_2 and H_2O fluxes are currently measured by two eddy covariance systems. One system monitors fluxes from the peatland with a relatively unaltered water table, the second monitors fluxes from the peatland with a raised water table. Each tower monitors air temperature/relative humidity (HMP45C, Campbell Scientific, Logan, UT), net radiation (NR-LITE, Campbell Scientific), soil heat flux (HFP01SC-L, Campbell Scientific) and storage (TCAV, Campbell Scientific), and solar radiation (CMP3, Campbell Scientific), windspeed and wind direction (CSAT3, Campbell Scientific), CH_4 (LI-7700 open path analyzer) and CO_2 and H_2O (LI-7500, LI-COR, Lincoln, NE) and rainfall (TE525, Campbell Scientific). All data are stored on a datalogger (e.g. CR3000 (unaltered site), CR5000 (site with raised water table, Campbell Scientific). A third eddy covariance tower was installed at a site with a lowered water table from 2010-2011. That site monitored air temperature/relative humidity (HMP45C, Campbell Scientific, Logan, UT), net radiation (NR-LITE, Campbell Scientific), soil heat flux (HFP01SC-L, Campbell Scientific) and storage (TCAV, Campbell Scientific), windspeed and wind direction (CSAT3, Campbell Scientific, CO_2 and H_2O (LI-7500, LI-COR). All data were stored on a datalogger (CR5000 Campbell Scientific)
7. **Installed micromet towers to measure plot scale ET**. At sites A&B (Fig. 1) we installed instruments measuring the relative humidity (CS500, Campbell Scientific) and soil temperature profile (copper constantan thermocouples at 1, 5, 10, 20, 50 cm – 2 per

site). We are using a 2-D sonic anemometer and net radiometer (CNR2-L, Campbell Scientific). Sapflow sensors were installed in plot A in 2011..

8. **Measured baseline ecosystem carbon cycling at all sites.** At each site, 8 steel collars were inserted into the peat to measure biweekly ecosystem carbon, water fluxes and methane.
9. **Installed OTC's in long-term water manipulated areas.** We have installed 4 OTC chambers at each long-term water manipulated area (total of 48 OTC chambers installed).
10. **Installed a short-term warming experiment.** We had two goals for our short-term warming experiment, 1) to quantify how warming influence peatland ecosystems, and if different types of experimental warming (warming lamps vs. open top chambers) produce different results. To answer these goals we established 18 plots (200 cm^2) and divided them into 3 treatments comprised of equal numbers of heating lamps, open top chambers, and control plots at Pequaming (Fig. 3). The replicates of each treatment were split equally between hummocks and lawns. Plexiglass hexagon open top chambers (OTC's) were designed according to ITEX (International Tundra Experiment) specifications. We also manipulated air and soil temperatures using adjustable, thermal infrared heating lamps (~ 2 m in length, Kalglo Inc. IR lamps [120V, 1500 W, 12.5 amps]) suspended 1.25 m above the moss surface. We picked the Pequaming site over SNWR because of its accessibility to nearby power sources.

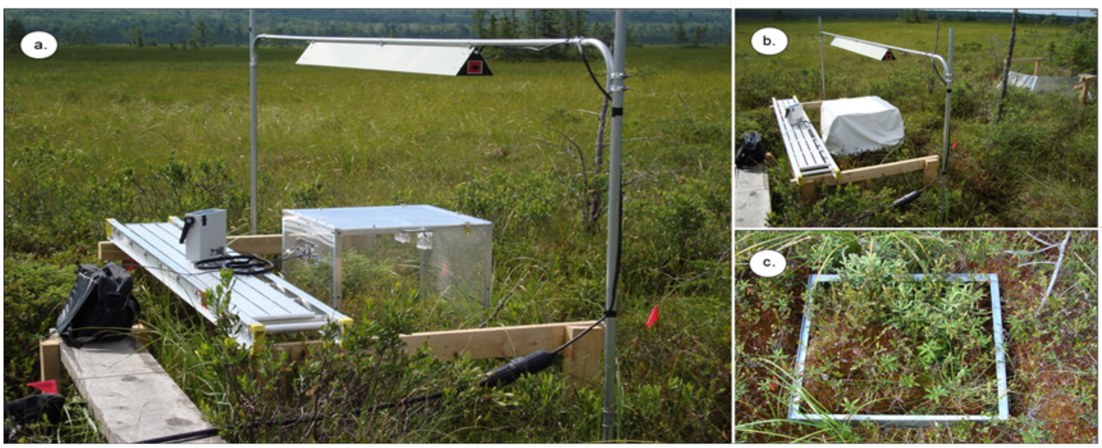


Figure 3. a. Gross ecosystem photosynthesis measurement (GEP) under an infrared heat lamp. b. A cover is placed over the chamber to block out daylight to record ecosystem respiration (ER). c. Galvanized steel soil collar inserted into the peat used for placement of the chamber.

11. **Collected soil cores for analysis.** Replicate soil samples were collected and are being analyzed for total carbon pools and standard peat physical properties, testate ameba, lead 210 dating, carbon dating, and carbon quality.
12. **Installed decomposition bags.** Decomposition bags were installed at multiple depths at sites.
13. **Installed cranked wires**. Replicate cranked wires were installed at all sites to measure sphagnum moss production.
14. **Initiated a historical analysis.** We have done an historical aerial photos interpretation and cored trees to quantify if peat draining facilitated tree invasion.

<u>3. Research Highlights</u> - In summary, our results indicate that peatland carbon cycling is influenced by temperature and long term hydrological changes, and further modified by microtopographic landform and vegetation. At Pequaming, we found that IR lamps increased soil and canopy temperatures more than OTC's (Table 1). Overall, warming slightly increased NEE by increasing GPP more than ER (Table 1). However, plant production varied by species. Leatherleaf decreased, sedge was not affected, and mosses increased CO_2 uptake with warming. Warming also slightly increased CH_4, but the results were not significant (Table 1).

Table1. Average (SE) canopy and peat temperature (C), ecosystem flux (umol m[2] sec[1]) and CH_4 (mg m[2] hr[1]) of warming treatments during 2009 and 2010 at Pequaming. Peat temperature were recorded at 5 cm depth. Average leatherleaf, sedge and moss CO_2 uptake during 2010 (umol m[2] sec[1]).

Measurement	Control	OTC	Lamp
Canopy temperature	19.1 (0.2)	18.7 (0.2)	21.5 (0.2)
Peat temperature	20.9 (0.6)	19.9 (0.6)	23.1 (0.5)
NEE	2.76 (0.1)	3.16 (0.1)	4.01 (0.1)
ER	3.16 (0.2)	3.73 (0.1)	3.45 (0.2)
GPP	5.93 (0.2)	6.89 (0.1)	6.96 (0.3)
CH_4	0.27 (0.1)	0.36 (0.1)	0.44 (0.1)
Leatherleaf	8.37 (2.0)	7.05 (1.7)	6.86 (1.3)
Sedge	7.18 (1.9)	6.53 (1.8)	7.24 (1.6)
Sphagnum moss	5.13 (1.2)	4.90 (0.8)	14.0 (2.4)

Average water table levels in SNWR reflected long term hydrologic alterations (Table 2), which modified carbon cycling. Using a combination of eddy flux towers and bi-weekly chamber data, we found that increasing the water table over a 70 year period increased NEE by lowering ER (Table 2, Figure 4). Higher water table levels also increased CH_4 emissions (Table 2). Conversely, lowering the water table decreased NEE by increasing ER more than GPP. CH_4 emissions decreased with a decreasing water table level (Table 2). Both increasing and decreasing the water table levels increased DOC concentrations compared to the control water table level (data not shown). We also found plant community changes have occurred due to the hydrological alterations, which also influenced carbon cycling (data not shown). In control water table sites, warming decreased NEE by lowering GPP and increasing ER. Conversely, NEE increased slightly with warming in either the higher or lower water table sites. Warming had mixed affects on CH_4 emissions (Table 2).

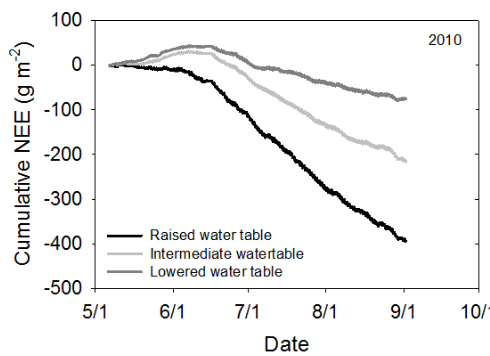


Figure 4. Cumulative NEE during the snow free season in 2010.

Table 2. Average environmental parameters and ecosystem C-fluxes (chambers) and eddy flux (eddy) for Seney during 2009-2010 arranged by water table and warming treatments.

Measurement	Control	Wetter	Drier
pH	3.77	3.90	3.70
Conductivity	63	49	76
WT (cm)	31	16	41
$NEE_{chambers}$ (umol m[2] sec[1])			
Ambient	2.01 (0.18)	2.23 (0.14)	1.81 (0.15)
OTC warming	1.63 (0.14)	2.44 (0.15)	2.22 (0.19)
$ER_{chambers}$ (umol m[2] sec[1])			
Ambient	2.43 (0.14)	2.02 (0.12)	3.01 (0.17)
OTC warming	2.51 (0.15)	2.31 (0.12)	3.24 (0.17)

$GPP_{chambers}$ (umol m^2 sec^1)			
Ambient	4.42 (0.25)	4.26 (0.21)	4.83 (0.19)
OTC warming	4.14 (0.19)	4.75 (0.19)	5.44 (0.24)
$CH_{4chambers}$ (mg m^2 hr^1)			
Ambient	0.38 (1.3)	0.63 (2.6)	0.13 (0.6)
OTC warming	0.40 (1.5)	0.44 (1.4)	0.21 (0.7)
$NEE_{eddyflux}$ (g m^2 season) 2010[1]:2011[2]	215:152	393:418	75:108

[1] data from 6 May to 31 August 2010
[2] data from 16 June to 15 September 2011

4.Research Products - The current web page is:
http://forest.mtu.edu/faculty/chimner/wetlandlab/carboncycling.htm.

5. Publications

Papers in Preparation/Submission.

Johnson, C.P., Hribljan, J.A., Chimner, R.A., Pypker, T.G. Open top chambers and infrared lamps: A comparison of heating efficacy and CO_2/CH_4 dynamics in a sub-boreal peatland. Submitting to Global Change Biology in winter of 2012.

Aljaste, A., Johnson, C.P., Hribljan, J.A., Pypker, T.A., Chimner, R.A. Warming alters photosynthetic rates of sub-boreal peatland vegetation. Submitting to Mires and Peat in winter of 2012.

Veverica TJ, Kane ES, Kasischke ES. Tamarack and black spruce adventitious root patterns are similar in their ability to estimate organic layer depths in northern temperate forests. Submitted to Canadian Journal of Soil Science in November 2011.

Ballantyne, D. Chimner, R.; Hribljan, J. Long-Term Water Table Manipulations on Peatland Carbon Fluxes. Submitted to Biogeochemistry in December of 2011.

Hribljan, J.A. and R.A. Chimner. Vegetation structure along a long-term water table gradient in a sub-boreal peatland. In preparation for submission to Wetlands winter 2012.

Hribljan, J.A., E.S. Kane, T.G. Pypker and R.A. Chimner. Dissolved organic carbon dynamics in a peatland after long-term water table manipulations. In preparation for submission to Ecohydrology winter 2012.

Hribljan, J.A. and R.A. Chimner. Peat substrate quality after long-term water table alterations in a northern peatland. In preparation for submission to Soil Biogeochemistry winter 2012.

Pypker, T.G., Boisvert, E.A., Paesalu, M., Chimner, R.A., Hrijblian, J.A. Initiation and development of three Lake Superior peatlands. In preparation for submission to Great Lakes Research winter 2012.B.

Presentations

Chimner, R., T. Pypker, M.M. Turetsky, J. Hribljan, M. Waddington (2008). Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resilience to climate change. American Geophysical Union, Fall Meeting, abstract #B13A-0429

Chimner, R.A. (2008). Peatlands and Climate Change. NIACS Climate Change conference to Ottawa National Forest. Michigan Tech University. (INVITED SPEAKER)

Hribljan J.A. and R.A. Chimner. (2008). Comparison of warming treatments in an Upper Michigan peatland. Poster presented at Ecology and Identification of Sphagnum. August 2008, Alaska.

Chimner, R.A., J. Hriblan, D. Ballentyne and C. Johnson. (2009). Peatland carbon pools in Michgan's UP and their response to climate change. Carbon in Northern Forests: integration of research and management. June 10 - 11, 2009, Traverse City, MI.

Chimner, R.A., Hribljan, J.A., Johnson, C., Ballentyne, D., Turetsky, M.M., Pypker,T.G., Waddington, M.J. (2009). Effects of Experimental Warming and Long-term Water Manipulation on Peatland Carbon Fluxes. The 2nd International Symposium: Peatland in the Global Carbon Cycle, Prague, Czech Republich, 25-30 September, 2009.

Hribljan, JA, RA Chimner, MM Turetsky, TG Pypker, MJ Waddington. (2009). Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resilience to climate change. EOS Transactions, AGU 89 (52) Fall Meeting Supplement, Abstract B13A-0429. (poster)

Hribljan, J.A., Chimner, R.A. (2009). Peatland Carbon Pools in Michigan's UP and their Response to Long-Term Drainage. Seney National Wildlife Refuge. August 15, 2009.

Chimner, R.A., J. Hriblan, D. Ballentyne and C. Johnson. (2009). Peatland Carbon Pools in Michigan's UP and their Response to Climate Change. Talk at Seney National Wildlife.

Hribljan, JA, RA Chimner, MM Turetsky, TG Pypker, MJ Waddington. (2009). Effects of plant species, organic matter quality, and microbial activity on peatland ecosystem function and resilience to climate change. – *displayed* at The Ecosystem Science Center 5th Annual Graduate Research Forum, Michigan Technological University, February 27, 2009.

Moore, PA, P Coulibaly, TG Pypker and JM Waddington (2010) Can machines learn to fill eddy flux data better than standard methods? – 3rd Joint CMOS-CGU Congress, Ottawa, Ontario, Canada, May-June 2010.

Ballantyne, D., Chimner, R. and Hribljan, J. (2010) The effects of long term water table manipulations on carbon fluxes at the seney national wildlife refuge. Society of Wetland Scientists 2010 Annual Meeting. June 28-31st. Salt Lake City.

Johnson, C.P., Hribljan, J.A. and Chimner, R.A.; Pypker, T.G. (2010) A micrometeorological comparison of the heating efficacy of two methods for increasing ecosystem temperature. Society of Wetland Scientists 2010 Annual Meeting. June 28-31st. Salt Lake City.

Ballantyne, D. and Chimner, R. (2010). The effects of long term water table level manipulations on carbon fluxes from a Great Lakes peatland. Ecosystem Science Center

Ballantyne, D., Chimner, R.and Hribljan, J. (2010) Carbon cycling across a water table gradient at the Seney National Wildlife Refuge. Wisconsin Wetland Association 2010 Annual Meeting. Feb. 11 & 12, Eau Claire, Wisconson.

E. S. Kane; L. R. Mazzoleni; C. J. Kratz; J. A. Hribljan; C. P., Johnson; T. G. Pypker; R. A. Chimner. (2010). Dissolved organic carbon in peat porewater increases with warming: a field manipulation experiment in a northern temperate bog. AGU Fall Meeting; San Francisco B23E-0425.

Moore PA, Pypker TG, Hribljan JA, Chimner RA, Waddington JM. (2011). Contrasting peatland evapotranspiration along a hydrological gradient. Canadian Geophysical Union Annual Meeting, Banff, AB.

Hribljan, J.A., Chimner, R.A. Effects of long-term water table alterations on plant species, soil quality, pore water chemistry and carbon cycling in a Great Lakes peatland. Fall meeting 2011. Geological Society of America abstract, Vol 43, No.5, p 558.

Hribljan, J.A. and Chimner, R.A. Effects of long-term water table alterations on plant species, soil quality, and carbon cycling in a Great Lakes peatland. – *displayed* at the Seney National Wildlife Refuge visitor center summer 2011.

Pypker, TG, 2011. Climate change and sub-boreal peatlands – Swedish University of Agricultural Sciences, Alnarp Sweden, November 25, 2011.

Pypker, TG, P Moore, JM Waddington, JA Hribljan, B Ballantyne, RA Chimner. 2011. The impact of long-term changes in water table height on carbon cycling in sub-boreal peatlands, AGU 92 (52) Fall Meeting Supplement, Abstract B21A-0251.

6. Students Supported

1. John Hriblon, PhD Ecology at MTU under Rod Chimner and Merritt Turetsky. (Graduating spring 2012)
2. Drew Ballentyne, MS Ecology at MTU under Rod Chimner. (Graduated winter 2010: Thesis title: The effects of long-term water table manipulations on carbon cycling in a Great Lakes peatland).
3. Chris Johnson, MS Ecology at MTU under Rod Chimner and Tom Pypker (Graduated summer 2011: Thesis title: Open top chambers and infrared lamps: A comparison of heating efficacy and CO_2/CH_4 dynamics in a Lake Superior coastal peatland).
4. Elizabeth Boisvert, MS Ecology at MTU under Tom Pypker. (Graduated summer 2009: Thesis title: Initiation and development of three lake superior coastal peatlands)
5. Paul Moore, PhD at McMaster University under Mike Waddington (Graduating Fall 2012)
6. Arvo Aljaste, MS Ecology at MTU under Rod Chimner (Graduated spring 2011: Thesis title: Warming alters photosynthetic rates of sub-boreal peatland vegetation).
7. Margus Paesalu MS Ecology at MTU under Tom Pypker (Graduated summer 2011: Thesis title: Tracing the source of groundwater for three different coastal peatlands along Lake Superior).

We have also supporting several undergraduate students who worked with our graduate students.

Improving prediction of climate change impacts on wetland-rich landscapes: Testing model mechanisms with flux-data assimilation at multiple sites

Ankur R Desai, Dept of Atmospheric & Oceanic Sciences, University of Wisconsin-Madison
D. Scott Mackay, Dept. of Geography, State University of New York - Buffalo

Final report (9/1/2007-6/30/2010)

Abstract

Ecosystem carbon cycle models fail to explain interannual variability in CO_2 fluxes in the upper Midwest. One possible reason is lack of model mechanisms for wetland biogeochemistry and hydrology. Moreover, wetlands are expected to be highly sensitive to climate change. In this project, we studied wetland and regional carbon cycles in a north temperate landscape. A decade long record of wetland flux and micrometeorology was collected and analyzed for climatic controls on wetland NEE. Further, these data were assembled with a regional network of wetland and upland biogeochemical data to quantify the role of wetlands in regional carbon cycling. Together these data were then used to evaluate and constrain a range of ecosystem models using both traditional and Bayesian parameterization and optimization techniques. Results from these studies have led to 16 peer-reviewed manuscripts and 32 conference presentations, supported training of 2 Ph.D., 5 M.S., and 2 undergraduates, and invigorated a new push by the ecosystem modeling community to improve representation of temperate and boreal wetlands in global carbon cycle models.

Research Activities (objectives, deviations, timeline)

The objective of this proposal was to develop a wetland-landscape model and assimilate long-term multiple flux tower observations to simulate wetland and upland mechanisms simultaneously. Research activities focused on 1.) analysis of observed flux tower data on environmental controls on NEE, especially of wetlands, 2.) development and parameterization of an existing model, with development of wetland biogeochemistry and hydrology routine, and 3.) evaluation of how wetlands in general are modeled in ecosystem carbon cycle simulations.

We outlined these specific tasks in the proposal:

1) Identify optimal physically based model(s) of upland/wetland carbon and water cycles following these iterative steps:
    a. Analyze observed regional upland and wetland CO_2 and H_2O eddy covariance flux data to discern key mechanisms and parameters to induce models for evaluation.
    b. Implement mechanistically predictive models of upland/wetland carbon & water cycles.
    c. Apply MCMC simulations, in single or multiple site mode, to the induced models for parameter and uncertainty estimation conditioned on observed data.
    d. Perform model checking with residual analysis and evaluate model performance with unassimilated eddy covariance flux data.

  e. Use deviance information criterion (DIC) to compare the performance of the induced models to the original model.

2) Combine ecosystem specific optimal models to construct a regional flux model, parameterize the regional model with multiple site data and high resolution land cover maps of the region, and evaluate against independent regional flux data.
3) Predict future response of the region's ecosystems to climate change and compare with the predictions obtained using other techniques.

The initial portion of the project focused on Task 1. While our initial proposal focused on one model, much of our research and engagement with the larger carbon cycle community led us to also evaluate a range of models and techniques for understanding wetland carbon cycling, especially under the auspices of the North American Carbon Program synthesis activities. These models were also used in regional upscaling studies to address Task 2. Finally, projections of model sensitivity were analyzed to understand future ecosystem response in wetter or drier climates.

Details of particular activities are noted below:

A. Collect and analyze observed wetland flux tower data

<u>A.1.) Collected flux tower, water table, and micrometeorological data</u>

Consistent with our original plans, we continued to operate the Lost Creek wetland flux tower and supplement support for the WLEF tall tower. The challenging wetland flux tower site still continues to be one of the few wetland sites in the Ameriflux network and among a limited set in the Fluxnet network. Data collected with support here has allowed for a decade long time series of half-hourly net ecosystem exchange and micrometeorology in a shrub alder fen that has experienced significant drying followed by a wetter period (Fig. 1). Also obvious in Figure 1 is the challenges required in long-term operation of a wetland tower operating on boardwalks and with solar power. Significant gaps in winter data occurred due to gas analyzer and data logger failures. Power system and data logger issues prevented much data collection in 2009.

Nevertheless, significant findings have been made with these data, which whn gap-filled and aggregated to seasonal scales, reveals an interesting interplay between gross primary production (GPP) and ecosystem respiration (ER), whose significant interannual variability operate in opposing directions, leading to limited variability in net ecosystem exchange (NEE) (Fig. 2). Currently we are analyzing the results of a stark shift in water table response after 2008. In spring 2010, a new beaver dam was found at Lost Creek and given the ample precipitation this spring, the water table has begun to rise. The initial response appears to be consistent with a linear response in water table and GPP and ER, which have both reversed trends.

<u>A.2.) Quantified response of northern fens and bogs respond to inter-annual fluctuations in water table</u>

Our initial analysis at the shrub wetland revleaed strong relationship of ER to water table elevation (Fig. 3) and these results were published in Sulman et al. (2009). A follow-up study expanded the analysis to a set of temperate and boreal fens and bogs with multi-year NEE and water table observations. Fens and bogs represent two common peatland ecosystem types in boreal and subarctic regions. Eddy-covariance measurements of carbon fluxes were obtained from six northern temperate and boreal peatland sites in Canada and the northern United States of America, representing both bogs and fens. The two peatland types had opposite responses of gross ecosystem photo- synthesis (GEP) and ecosystem respiration (ER) to inter-annual fluctuations in water table level. At fens, wetter conditions were correlated with lower GEP and ER, while at bogs wetter conditions were correlated with higher GEP and ER (Fig. 4). We hypothesize that these contrasting responses are due to differences in vegetation functional diversity between the two peatland types. Because of their richer nutrient status, fens can support generalist plants that respond positively to drier soils, and can recruit shrubs during periods of water table decline. The low nutrient status of bogs limits them to obligate wet- land species that are adapted to the unique chemical and hydrological characteristics of bogs, and these species are less likely to be resilient to drier conditions. The coherence of our results between sites representing a range of average environmental conditions indicate ecosystem-scale differences in resilience to hydrological changes that should be taken into account when considering the future of peatland ecosystem services such as carbon sequestration under changing conditions.

B. Assess observations of regional carbon cycle

B.2) Found shoulder climate and phenology drive coherent regional interannual variability

A second goal of our proposal was to understand how variable climate sensitivity was among multiple ecosystems found in wetland-rich landscapes. We performed observational data analysis on flux tower data from the set of spatially co-located upland and wetland sites. Analysis of ecosystem respiration and water table elevation at upland and wetland sites shows that the threshold response of carbon fluxes to water table elevation is distinct to wetlands. The threewetland sites show similar large increase in magnitude of CO_2 efflux as water table declines pass 20 cm.

Further, the multi-year eddy covariance carbon dioxide flux observations from five of these ecosystems, located 400 km of each other and exhibiting coherent interannual variability (Fig. 5), were used to parameterize a simple ecosystem model using Markov Chain Monte Carlo assimilation techniques similar to those discussed in the proposal (Desai, 2010). The model, when properly constrained with an interannual sensitive cost function, was able to explain a significant proportion interannual variation of carbon fluxes in all ecosystems except the old-growth forest (Fig. 6). The results reveal that spring or autumn climate thresholds that drive phenology variations in annual carbon uptake, though the magnitude and strength varied by site.

B.1.) Analyzed climatic controls of interannual variability in regional carbon fluxes

We also asked to what extent are these coherent site level observations reflective of what we observe at the regional scale. Observations of regional net ecosystem exchange (NEE) of CO2 for 1997-2007 were analyzed for climatic controls on interannual variability (IAV) across northern Wisconsin (Desai et al., 2010). Four independent techniques were applied to quantify monthly regional NEE for a 10^4 km^2 area. These techniques included two bottom-up methods, based on flux tower upscaling and forest inventory based demographic modeling, respectively, and two top-down methods, based on tall tower equilibrium boundary layer budgets and tracer-transport inversion, respectively. While all four methods revealed a moderate carbon sink, they diverged significantly in magnitude, though coherence of relative magnitude and variability of NEE anomalies was strong across the methods. The strongest coherence was a trend of declining carbon sink since 2002. Most climatic controls were not strongly correlated with IAV.

Significant controls on IAV were those related to hydrology, such as water table depth, and atmospheric CO2 (Fig. 7). Weaker relationships were found with phenological controls such as autumn soil temperature. Hydrologic relationships were strongest with a 1-year lag, potentially highlighting a previously unrecognized predictor of IAV in this region.

B.3.) Constructed a complete aquatic-terrestrial-anthropogenic carbon budget

Results form modeling and regional assessment activities above provided a means to construct regional carbon budgets. Further collaboration with limnologists from the North Temperate Lakes Long Term Ecological Research site allowed us to extend our analysis to lakes. Using a combination of field surveys and tower-based CO_2 flux measurements, modeling, and published literature, we constructed a complete C budget for the Northern Highlands Lake District (NHLD), a ~6400 km^2 lake and wetland rich region in northern Wisconsin/Michigan (Buffam et al., 2011). This is one of the first regional C budgets to explicitly incorporate aquatic and terrestrial C cycling under the same framework. We divided the landscape into 3 major compartments (forests, wetlands and lakes) and quantified all major C fluxes into and out of those compartments, with a particular focus on atmospheric exchange but also including sedimentation in lakes and hydrologic export. Landscape C storage was dominated by peat-containing wetlands and lake sediments, which make up only 20% and 13% of the landscape area, respectively, but contain >80% of the total fixed C pool in the NHLD (ca. 400 Tg) (Fig. 8). We estimated a current regional C accumulation of 1.1±0.1 Tg yr^{-1}, about 7 times the regional fossil fuel emissions in this sparsely populated area. The largest net surface-atmosphere flux was forest net ecosystem exchange (NEE), into aggrading forests for a total of 1.0±0.1 Tg yr^{-1}. Mean wetland NEE (0.12±0.06 Tg yr^{-1} into wetlands), lake CO_2 emissions and riverine efflux (each ca. 0.03±0.01 Tg yr^{-1}) were smaller but of consequence to the overall budget. Hydrologic transport from uplands/wetlands to surface waters within the region was an important vector of terrestrial C, contributing to long-term C storage, CO_2 evasion, and riverine export. Regional C fluxes and pools would be misrepresented without inclusion of lakes and wetlands, and C budgets in heterogeneous landscapes open opportunities to examine the sensitivities of important fluxes to changes in climate and land use/land cover.

C. Develop and evaluate carbon cycle models for wetland-rich landscapes

C.1) Develop TREES for wetland and upland biogeochemistry and hydrology

Observational analysis was also supported by model development. Several lines of model development and application were conducted to better incorporate wetland biogeochemistry and hydrology into regional carbon cycle models. This activity included making improvements to the respiration logic in TREES, especially with regard to belowground processes, and developing an improved plant hydraulic sub-model in TREES that will provide a way to link both photosynthetic and rhizosphere processes directly to the hydrologic processes (e.g. groundwater-surface water coupling).

Several improvements to model logic in TREES were made to link photosynthetic and rhizosphere processes directly to wetland hydrology. An explicit coupling of groundwater and surface water has been incorporated around a three-layer logic consisting of a litter layer, a surface soil layer, and a deep layer bounded by a dynamic water table. Each successive soil layer receives drainage from the layer above and capillary recharge from the water table below. The soil water model component has been validated at various upland sites in the region. Evaporation occurs at variable rates from the litter and surface soil layers, while transpiration is taken from the soil layers based on root distribution and soil water potential in respective layers. Heterotrophic respiration is keyed to soil temperature and moisture, and is calculated for slow and fast pools in both surface and deeper soil layers. Root respiration is tied to soil temperature and plant-water relations (or carbon transport rate). In addition, a non-stomatal limitation on photosynthesis was developed that explicitly ties belowground processes controlling nitrogen cycling and root hydraulic conductance to gross primary production. This new model logic has been rigorously tested at upland (Willow Creek) and wetland (Lost Creek) sites.

C.2) Develop regional ecosystem MCMC parameter estimation techniques
To allow for observations to inform model structure and parameters, we developed a Markov Chain Monte Carlo shell, based on the algorithms embedded in TREES, to facilitate Bayesian analysis with multiple towers. This shell includes the model complexity penalties (i.e. DIC), which will allow us to rigorously find the simplest model structure needed to predict net ecosystem exchange of carbon across full wetland to upland gradients.

TREES is now coupled to a customized MCMC shell for parameter estimation and error analysis. The shell includes as one of its products the deviance information criterion (DIC) to compare the performance of an induced model to a reference model. Thus far we have focused our analysis on single flux towers at a time, but we have been testing several potential algorithms for parameterizing models with multiple site data by simultaneously evaluating both evapotranspiration and net ecosystem exchange at single sites. Two approaches are being used. One approach involves conditioning a single parameter covariance matrix, but with interlaced chains that each use independent likelihood functions and assimilated data. Each time the covariance matrix is updated the algorithm jumps to a new chain. For example, for assimilating evapotranspiration and net ecosystem exchange we maintain two chains. The alternative approach has been to define a joint likelihood function. Both approaches are consistent with Bayesian analysis, but the former has two advantages. First, it is mathematically simpler for multiple sources of assimilated data, and second, it requires no prior weights to be assigned to each evaluation. Therefore, we think it has more potential to "learn" from the data provided. However, it has the disadvantage of requiring a larger number of computations.

For evaluation at both upland and wetland sites, we constrained leaf area index, specific leaf area, plant biomass, belowground biomass, and leaf nitrogen concentration in TREES with biological data available for Willow Creek and Lost Creek, respectively. We constrained plant hydraulic parameters for controlling plant canopy gas exchange using evapotranspiration and micrometeorological data for periods when the water table was low and no precipitation had recently occurred. We ran MCMCs on parameters that control the rate of heterotrophic respiration (optimal soil moisture and temperature, fast carbon pool fraction of measured total belowground carbon), root respiration (respiration coefficient for Q10), and soil texture (through porosity). We employed a novel technique we have developed to run multiple model structures with our MCMC shell, allowing for explicit testing (using DIC) of alternative mechanisms. Specifically, we defined four functional traits related to autotrophic and heterotrophic response to groundwater dynamics: 1) flooding constraints on root hydraulic conductance, 2) flooding constraints on canopy stomatal conductance, 3) non-stomatal limitation of photosynthesis in response to nitrogen source limitation and transport, and 4) controls on heterotrophic respiration. For non-stomatal limitation of photosynthesis we incorporated a link between microbial activity, nitrogen sinks, and root hydraulic conductivity for controlling nitrogen uptake.

Simulations with the parameterized model supported the finding by Sulman et al (2009, 2010) that evapotranspiration was responsive to water table depth. The model suggested that a decline in water flux as the water table dropped was due to reduced capillary rise to the soil surface during periods when there was insufficient precipitation to recharge the surface soil layer. Our modeling results show that the best models for the wetland site, in terms of DIC, are those that include a non-stomatal limitation on photosynthesis that is connected to water table dynamics. Figure A shows simulations of Lost Creek net ecosystem exchange of carbon, C_{NEE}, and evapotranspiration, E_T for the original TREES model lacking groundwater coupling to aboveground processes (a, b), and the modified model having the new mechanisms (c. d). For the upland site there was no detectable need for such a link between belowground processes and carbon assimilation. This provides support for a short-term response of gross ecosystem production to water table depth dynamics, and in turn a cumulative effect on carbon uptake and allocation that are reflected in the findings presented by Sulman et al (2009, 2010). Although heterotrophic respiration showed a large response to water table depth it represented only a small fraction of belowground respiration in comparison to root respiration, which showed primarily a response to soil temperature (Figure A). These findings were presented in initial form in an invited talk at the Spring AGU meeting (Mackay et al, 2009), followed up with revised findings in a Fall 2010 AGU presentation (Mackay et al, 2010), and are presently being developed into a manuscript (Mackay et al, in prep for Ag. Forest Met.) that is near completion.

Since ecosystem models rely heavily on parameterization derived from plots, we also tried to determine if plot size and location affected ability to accurately derive key ecosystem parameters such as canopy stomatal conductance (G_S), which is key to modeling gross primary production. A scaling analysis was conducted using spatially extensive sap flux measurements across a wetland-to-upland gradient in northern Wisconsin near the WLEF tower. Plot representativeness was dependent on location within the study area, especially along the sharpest transition between wetland and upland (Figure 9, taken from Mackay et al 2010, JGR). This also shows a clear justification for accurate portrayal of hydrologic feedbacks on canopy processes in models of evolutionary dynamics of ecosystems, which is needed for predicting future ecosystem responses. Moreover, G_S is strongly influenced by photosynthesis, which in turn depends on a combination of canopy light environment and belowground processes. Loranty et al (2010, JGR) showed with a 3-D canopy light version of TREES that photosynthetic light limitation was a strong control over spatial heterogeneity of G_S (Loranty et al, 2010 JGR, Figure 5).

<u>C.3) Evaluate TREES against flux tower observations</u>
MCMC simulations were successfully performed for Lost Creek and Willow Creek, in which both CO_2 and H_2O eddy covariance data have been assimilated using a joint likelihood function that gives equal weight to the squared errors of evapotranspiration and net ecosystem exchange, respectively. Our work on rhizosphere components of the model logic has improved the robustness of such predictions at diurnal timescale (Fig. 10). Nevertheless, the model parameterization was able to explain unassimilated eddy covariance data quite well when a full

representation of the water table was employed (Fig. 11). Indeed, the residuals (modeled NEE – measured NEE) show little bias or trends. Moreover, the 90% and 95% levels the posterior density regions include 86.6% and 95.6% of the raw measured NEE values, respectively.

Recent development as expanded our updated TREES model on a number of towers sites, including Mer Bleu bog, Willow Creek forest, and Lost Creek fen. TREES was modified further to handle byrophytes (Sphagnum moss) for Mer Bleu and other bog sites. We have been examining how important the representation of groundwater hydrology is for predicting carbon fluxes. At Lost Creek a model with no lateral groundwater dynamics (bucket model) tended to bias the carbon flux estimates, but a model with the correct water table dynamics did much better. Further improvements to predicted carbon fluxes were minimal when simultaneously assimilating evapotranspiration data.

One diagnostic of a useful model is that the modeled flux response, obtained using inputs that can (or are) measured, match the observed response at a level that is consistent with its intended purpose. Assuming that models that rely on measured inputs and less on parameterization would be more parsimonious, we examined using TREES with its MCMC shell the effects of withholding measured inputs. A multi-faceted analysis was conducted, which included the use of deviance information criterion (DIC), posterior distributions of parameters, and comparisons between predicted parameters and the withheld measured values. Withholding too much data exaggerated the performance of the model, as measured with DIC, but at the expense of losing the ability to correctly predict the withheld parameter values (Mackay et al 2011, accepted with minor revisions).

<u>C.4) Predict regional carbon cycles for northern Wisconsin</u>

While on sabbatical leave at the University of North Carolina – Chapel Hill, Mackay began work with distributed modeling using a new version of RHESSys that routes groundwater flow coupled with long-term carbon dynamics. The intention is to use this model for long-term evolutionary dynamics of northern Wisconsin (and other) systems to examine effects of changing climate and water balance on carbon dynamics. RHESSys is best suited for this, but it also lacks plant hydraulics needed to examine how different strategies for drought tolerance can lead to differences in canopy composition over time. For this we are using TREES with the modified plant hydraulics, which has been developed as part of this project. This process was supported by the assistance of an NSF Research Experiences for Undergraduates (REU) student from Stoneybrook University, Mary Friess. Mary has been doing database development and adapting RHESSys for northern Wisconsin landscapes. This work has continued since Fall 2010 by Ryan Stotz, a new M.S. student working with Mackay.

In parallel, we conducted Bayesian simulations of fluxes across virtual chronosequences encapsulated by aspen to mature hardwood to old-growth hardwood. The basic question was how far off would forest water use predictions be if a landscape was assumed to lie at one point along the chronosequence. The results are forthcoming in a refereed book chapter, “Consequence of stand age and species’ functional trait changes on ecosystem water use of forests,” in a volume edited by Rick Meinzer.

C.5) Evaluate wetland responses of global carbon cycle models

Precise model predictions of wetland carbon sequestration or expulsion are paramount to accurately diagnosing future concentrations of atmospheric carbon and the subsequent consequences to the climate system. However, significant model error exists in predicting these processes. Moreover, wet regions such as temperate wetlands are predicted to become wetter and warmer due to anthropogenic climate change. As part of a North American Carbon Program (NACP) site interim synthesis, nearly two dozen ecosystem models were parameterized and run at two dozen flux tower sites using a consistent set of forcing data and site-level initial conditions.

Three of these sites were wetlands, where seven of the models were run. We used this subset of the NACP synthesis to determine whether or not hydrology currently plays a prominent role in prediction error. Observations and models are Lost Creek reveal opposite responses of the models to high and low water tables and GPP and ER (Fig. 12). Across the two fen sites and one bog site, flux residuals (simulated – observed) were correlated with measured water table for both gross ecosystem productivity (GEP) and ecosystem respiration (ER) at the two fen sites, and were not consistently correlated with water table at the bog site (Fig. 13). While modeled diurnal cycles at fen sites agreed well with eddy covariance measurements overall, eddy covariance GEP and ER were higher during dry periods than during wet periods, while model results predicted either the opposite relationship or no significant difference. At the bog site, eddy covariance GEP had no significant dependence on water table, while models predicted higher GEP during wet periods. All models significantly over-estimated GEP at the bog site, and all but one over-estimated ER at the bog site. Carbon cycle models in peatland-rich regions could be improved by incorporating better models or measurements of hydrology and by inhibiting GEP and ER rates under saturated conditions. Bogs and fens likely require distinct treatments in ecosystem models due to differences in nutrients, peat properties, and plant communities. These results are being developed into a manuscript (Sulman et al., in prep) that we intend to submit in September.

Research Highlights

Figure 1. A decade long record of net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (ER) collected along with water table depth at the Lost Creek shrub fen flux tower reveals a complicated seasonal patterns of carbon exchange in face of seasonal and interannual variability in water table elevation.

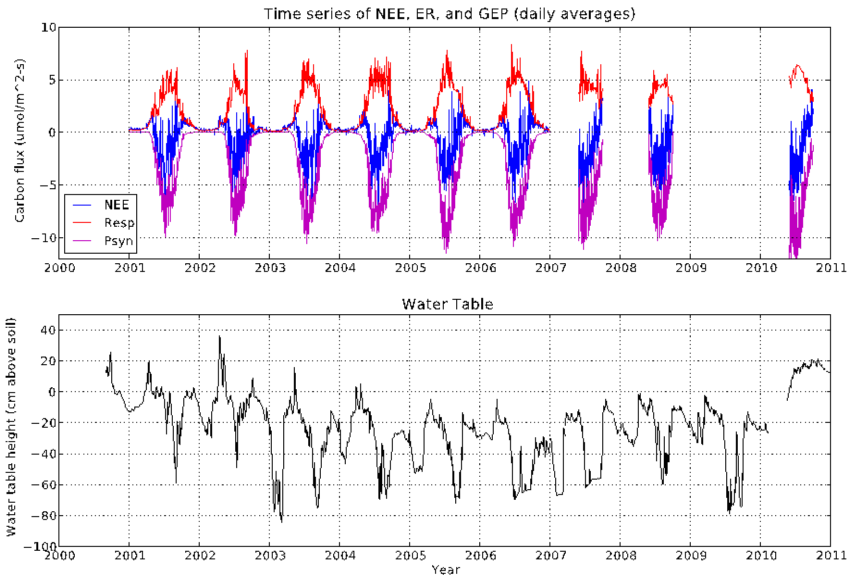


Figure 2. When growing season fluxes are summed, a few key features emerge – namely relatively small interannual variability in NEE is a consequence of relatively large but counterbalancing interannual variability in GPP and ER.

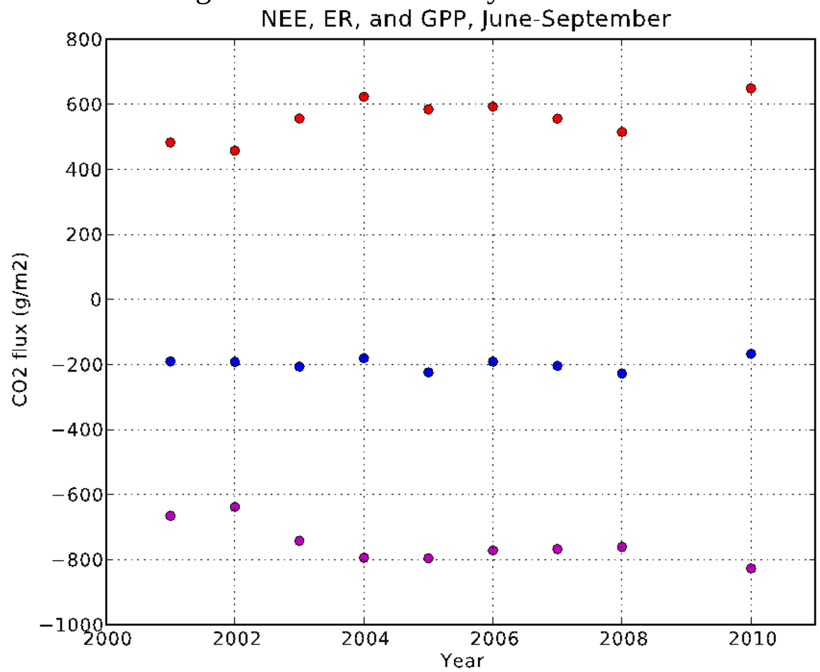


Figure 3. From Sulman et al (2009), relationship of ER at Lost Creek to water table depth and soil temperature shows a relatively consistent threshold response of significantly lower ER with increasing water table elevation, with limited soil temperature influence.

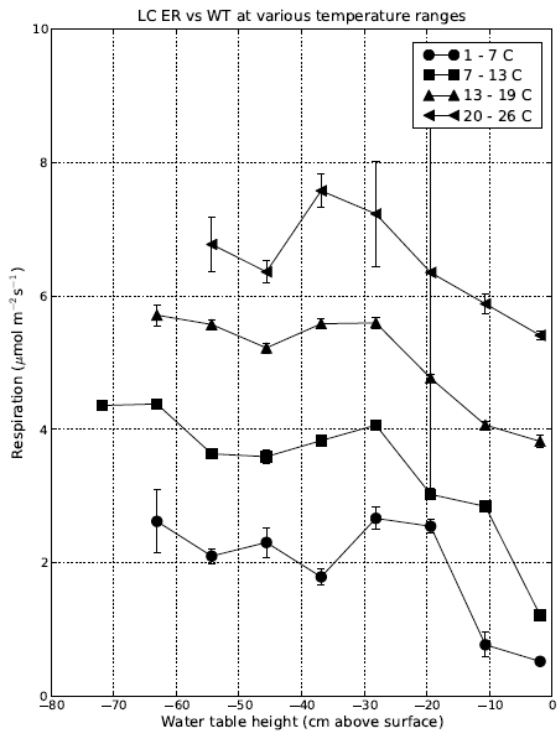


Figure 4. June-July-August average carbon flux anomaly at fen and bog sites as a function of growing season average water table anomaly from Sulman et al. (2010). Anomalies were calculated by subtracting the mean growing season value for the study period at each site. Fen sites are marked with black symbols, and bog sites with white symbols. Vertical error bars represent 95% confidence intervals. Water table measurements have an uncertainty on the order of a few cm due to spatial variations in site topography and water table level, but horizontal error bars are omitted in order to preserve clarity of the plots. The 2003 site-year at Ca-SDH-fen (stars) is shown, but was excluded from calculations. Ecosystem respiration anomaly was negatively correlated with water table anomaly at fen sites and positively correlated with water table anomaly at bog sites (a). Gross ecosystem photosynthesis anomaly was also negatively correlated with water table anomaly at fens and positively correlated with water table anomaly at bogs (b). Net ecosystem exchange anomaly was not significantly correlated with water table anomaly at fens or bogs (c).

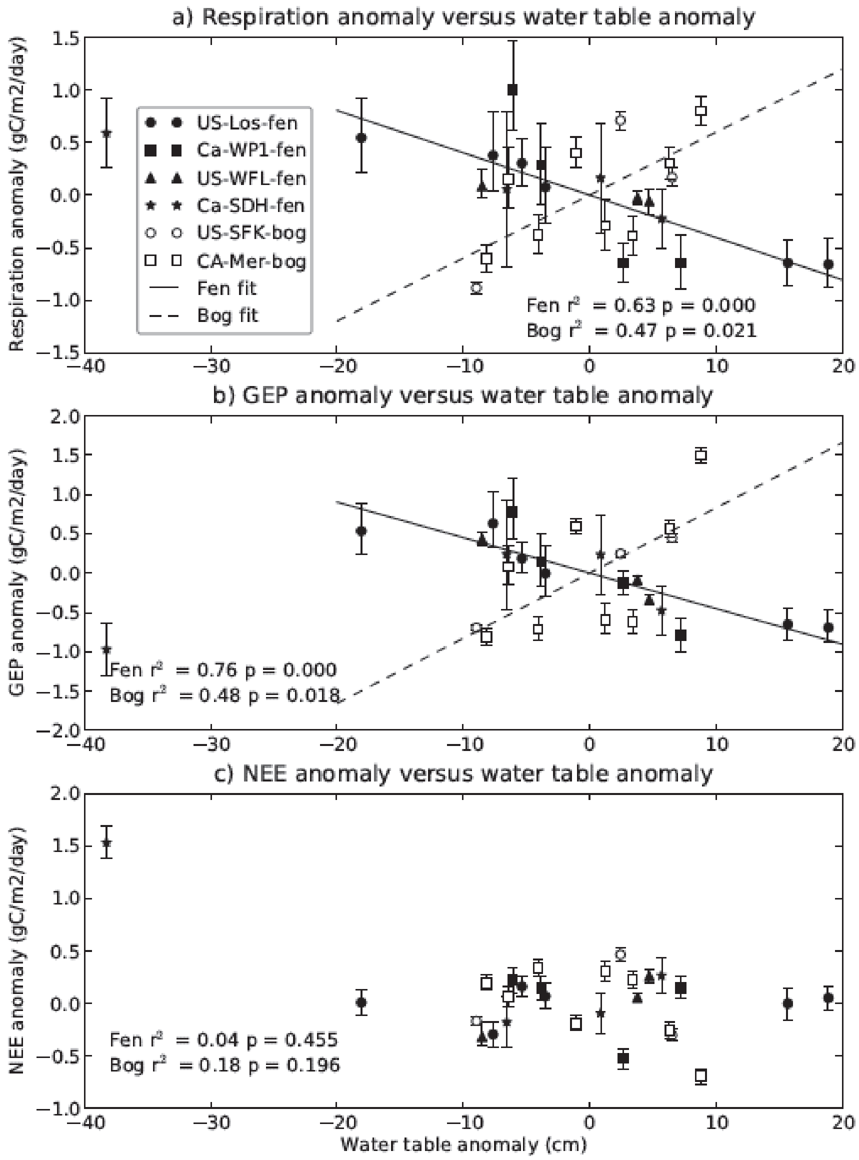


Figure 5. Observed standardized interannual variability in NEE at the five study sites. Strong coherence in variability in NEE was observed across the time period, even though absolute magnitudes in NEE variability varied widely. Observational uncertainty in NEE is noted by the horizontal bars.

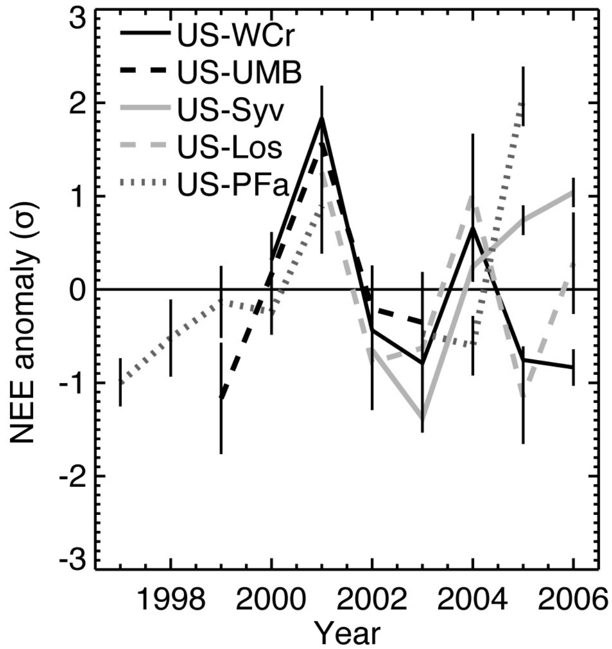


Figure 6. Correlation of anomalies in observed and modeled annual NEE using a) the traditional AH cost function parameters (Table 4) and b) the interannual sensitive AI cost function parameters (Table 5). Significant improvement in simulation of interannual variability was found for all sites in the latter.

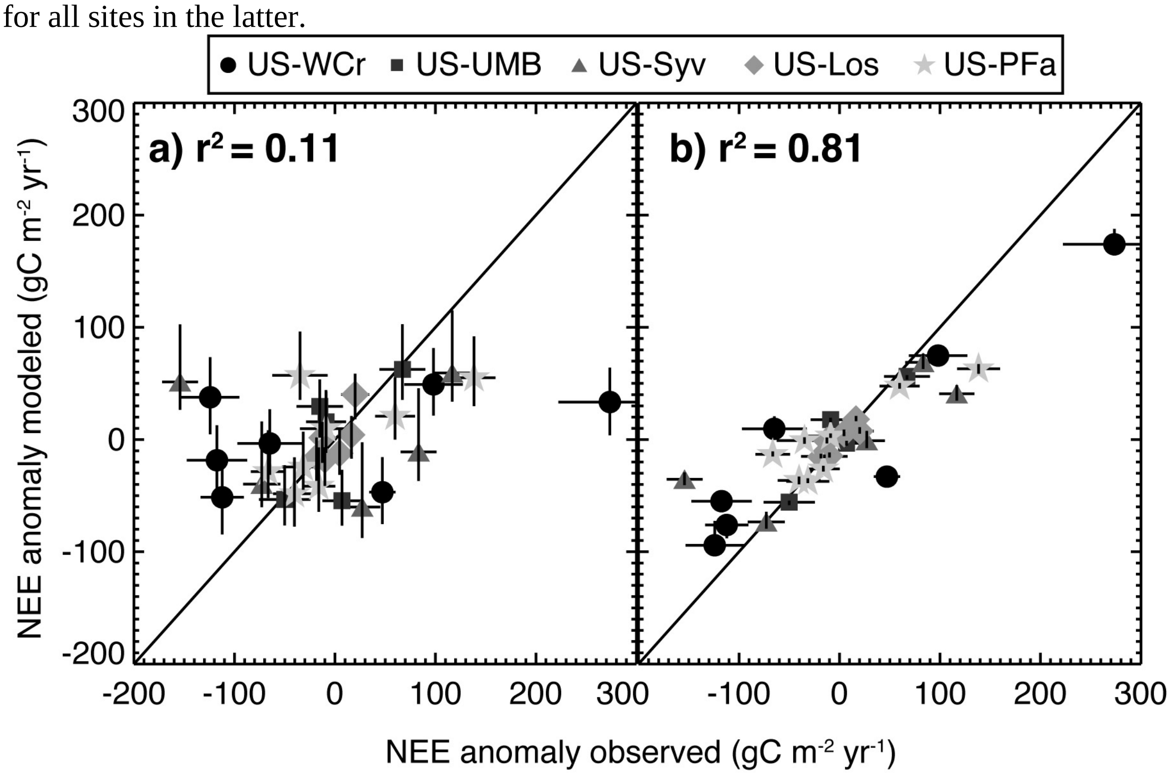


Figure 7. Scatter plot of annual NEE anomaly to (a) lag 1 year Qtable, (b) lag 1 year [CO2], (c) SON soil temperature, and (d) MAM PAR for bottom-up (left panels) and top-down (right panels) methods. Symbols are: IFUSE (filled circle), ED (gray diamond), EBL (square), CT (triangle). Top-down methods and IFUSE agree on slope of correlation, while ED generally differs.

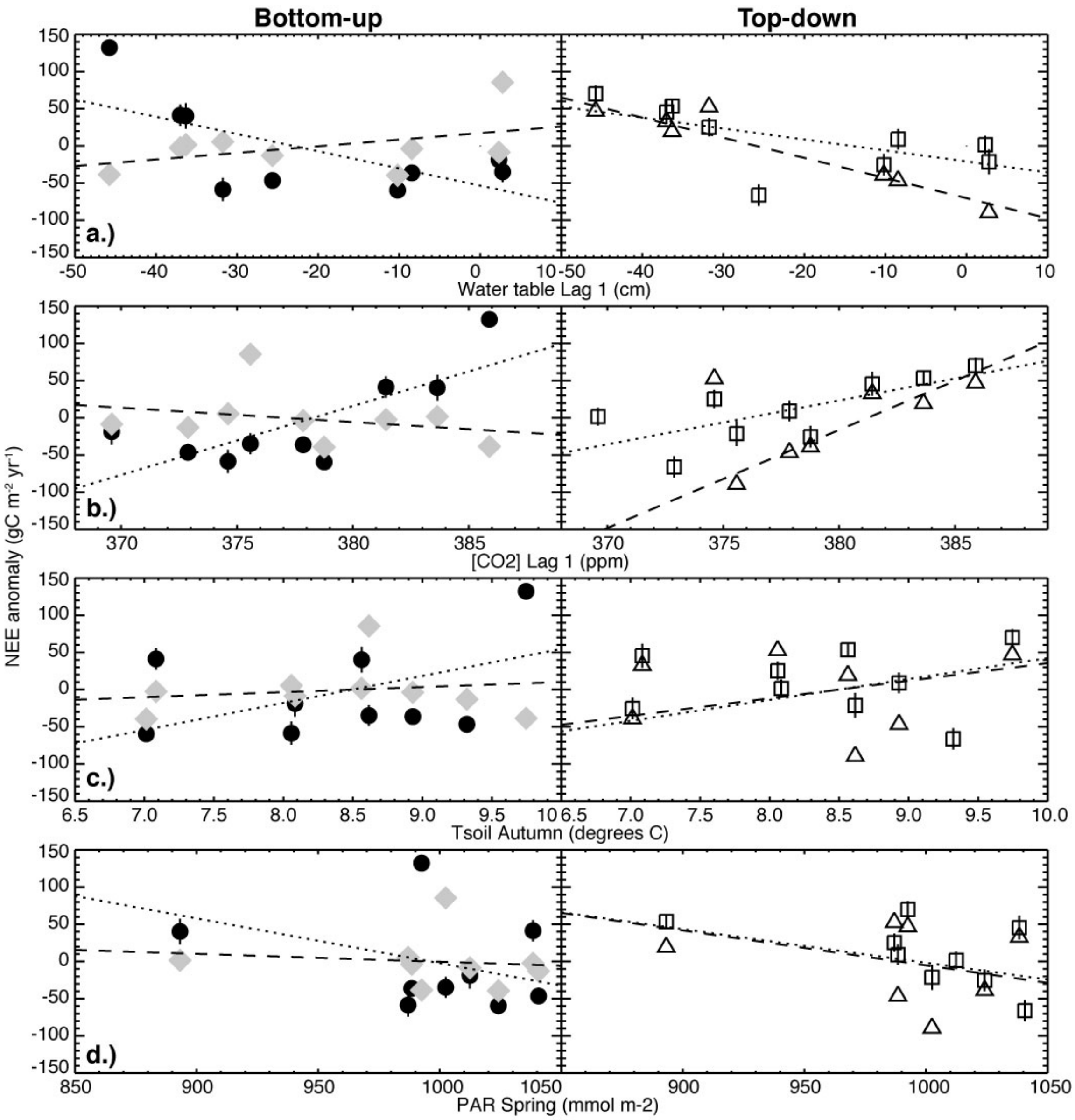


Figure 8. Illustration of spatial variation of carbon pools and fluxes on the landscape, for an 18 x 18 km region around the Trout Lake Field Station. In panel B, pool sizes were assigned by summing the soil/sediment C and vegetation C at a given location. This was achieved by combining the NRCS soils map for mineral soils and histosols (peatlands), the lakes map with modeled sediment pools, and the forest vegetation C pool using average values for each of 3 regional forest types from the USFS-FIA database. In panel C, average annual surface-atmosphere fluxes are visualized by assigning the average value to each terrestrial 30 x 30 m pixel in the NLCD map according to category, while lake fluxes were assigned at random from the distribution of values for each lake size category as described in the text. The 7 LTER lakes were assigned their measured long-term mean annual flux values.

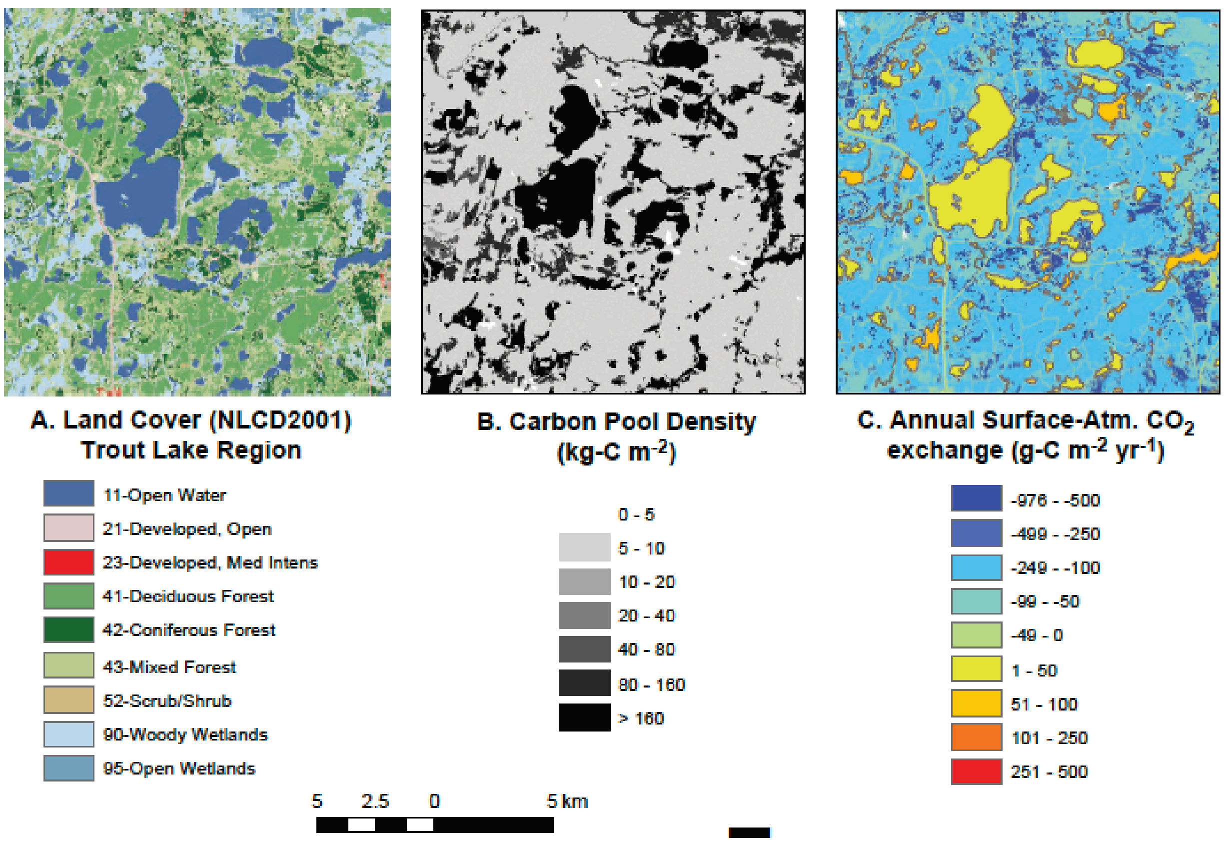


Figure 9. Illustration of how leaf area index, *L*, and reference canopy stomatal conductance, G_{Sref}, to canopy density calculated along a water table depth gradient, P_{CC}, for emergent aspen trees in northern Wisconsin. At high ground water table the relative open canopy (low P_{CC}) also has low stomatal conductance, which is contrary to what is expected from the standpoint of aboveground competition for light. This suggests a feedback between belowground processes and either a stomatal or non-stomatal limitation on the canopy processes. Reproduced from Mackay et al (2010, JGR).

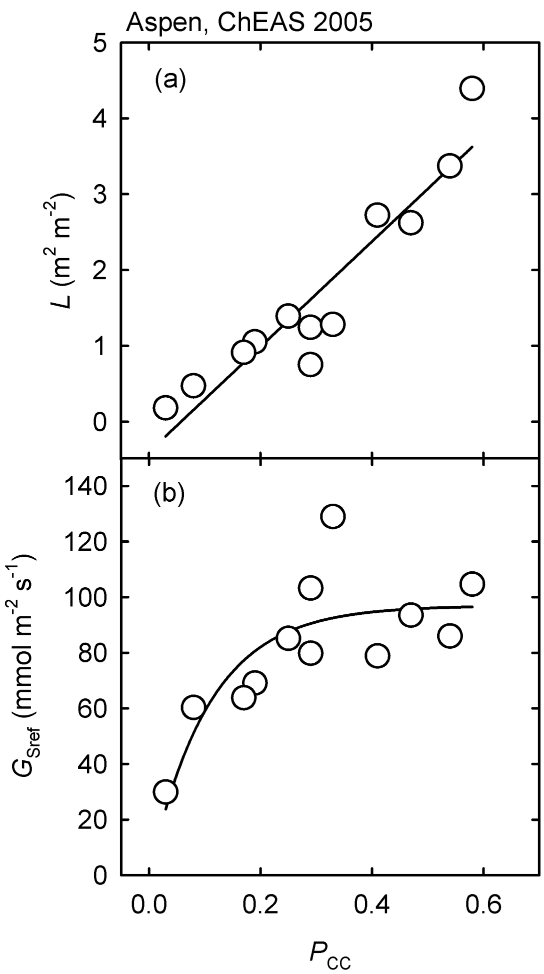
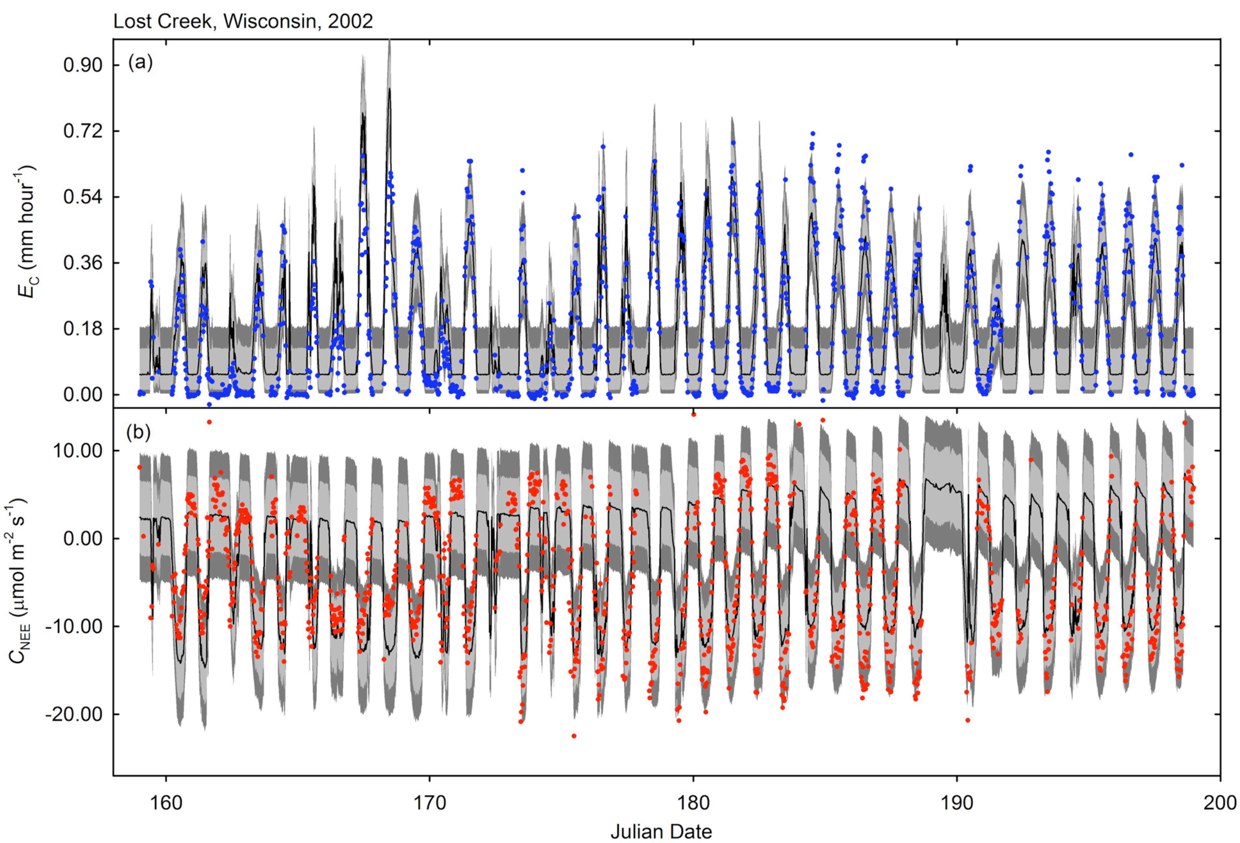


Figure 10. *Bayesian simulations of evapotranspiration,* E_C*, and net ecosystem exchange of carbon,* C_{NEE}*, using TREES applied to Lost Creek. Results in (a) and (b) are for a version of the model that did not have the modified belowground controls on autotrophic processes, including non-stomatal limitation of photosynthesis. Results in (c) and (d) are for a modified model structure that included these processes. The solid lines represent posterior mean values, light grey regions represent 75% posterior intervals, and dark grey zones represent the 95% posterior intervals. From left to right the water table is dropping almost monotonically from the surface at the beginning of the period to about 60 cm below the surface at the end of the period.*



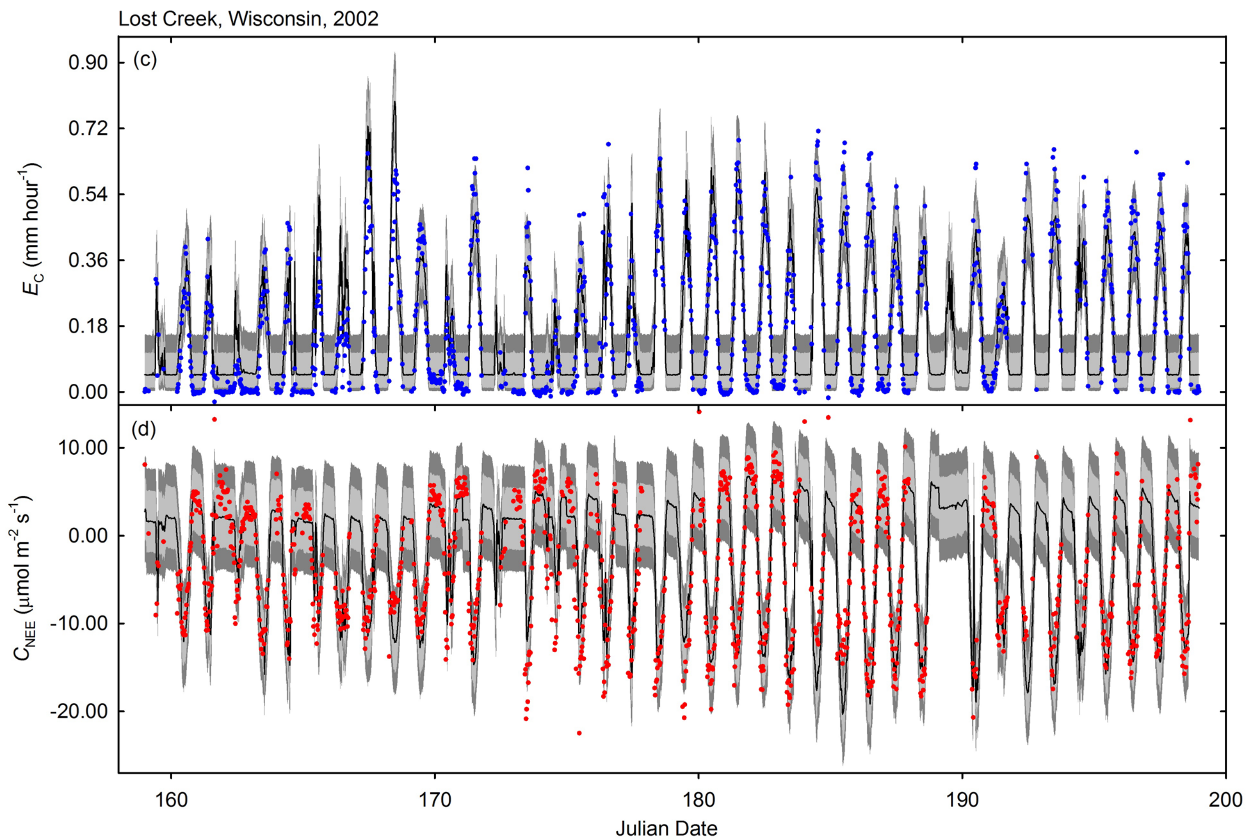

Lost Creek, Wisconsin, 2002
(c)
(d)
0.90
0.72
0.54
0.36
0.18
0.00
E_C (mm hour^{-1})
10.00
0.00
-10.00
-20.00
C_{NEE} (μmol m^{-2} s^{-1})
160
170
180
190
200
Julian Date

Figure 11. Simulations of net ecosystem exchange of carbon (NEE) for the Lost Creek fen for (a) bucket hydrology, (b) 3-D hydrology, and (c) 3-D hydrology in which evapotranspiration (ET) is assimilated along with NEE. The simulations are based on 40 consecutive days at 30-minute time steps and summarized here as diurnal ensembles. 95% posterior intervals and means were generated from 8000 simulations sampled from 4 MCMC chains.

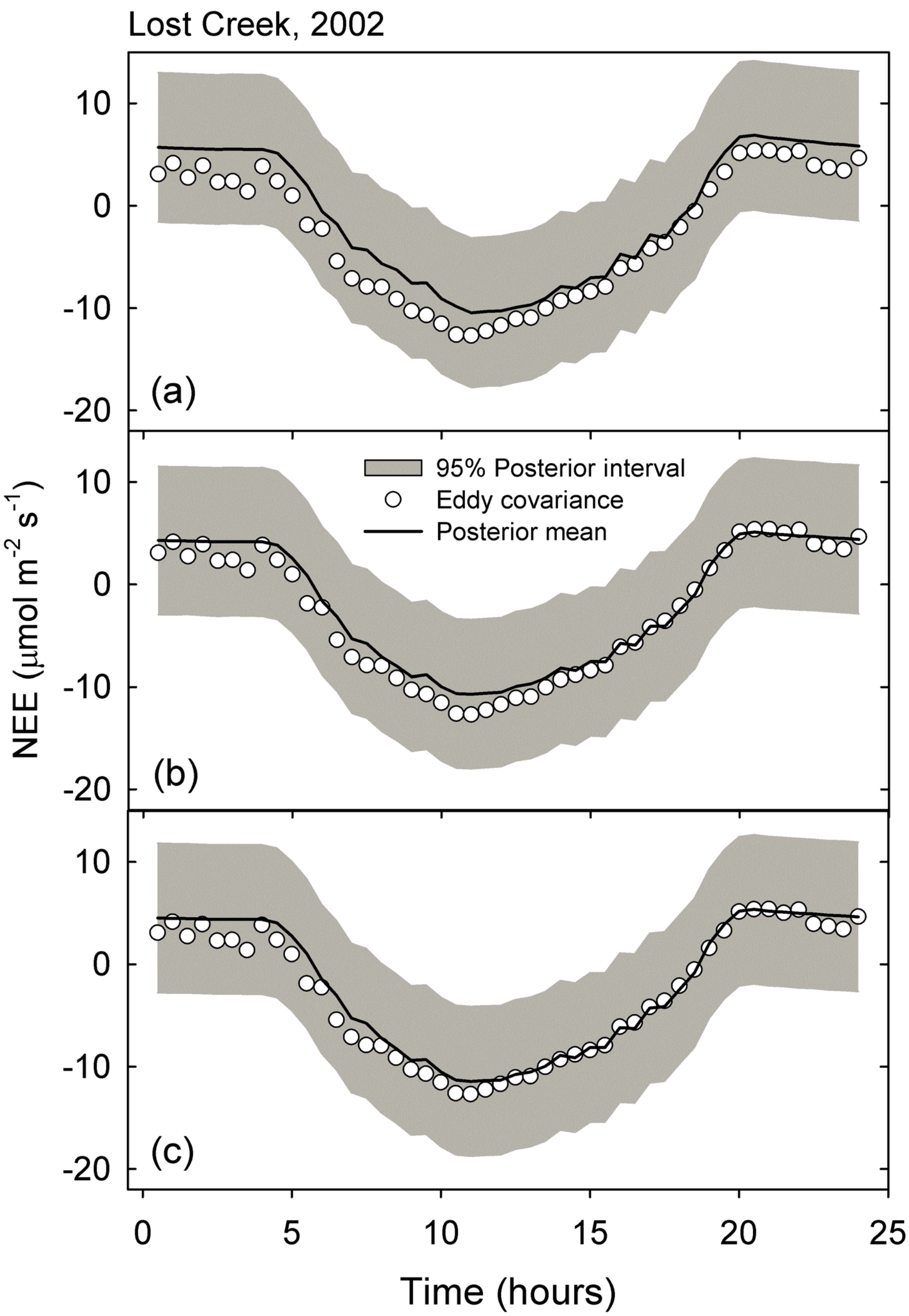


Figure 12. Mean summer diurnal cycles of ecosystem respiration (ER) and gross ecosystem production (GEP) at Lost Creek shrub fen. ER is positive, and shown with dotted lines. GEP is negative, and shown with dashed lines. Only non-gap-filled data are included. Error bars indicate 95% confidence intervals on the mean of each bin. Blue and red curves include eddy covariance data from weeks in the top and bottom 30th percentiles of water table height, respectively. Green and orange curves include modeled NEE from weeks in the top and bottom 30th percentile of modeled soil moisture, respectively.

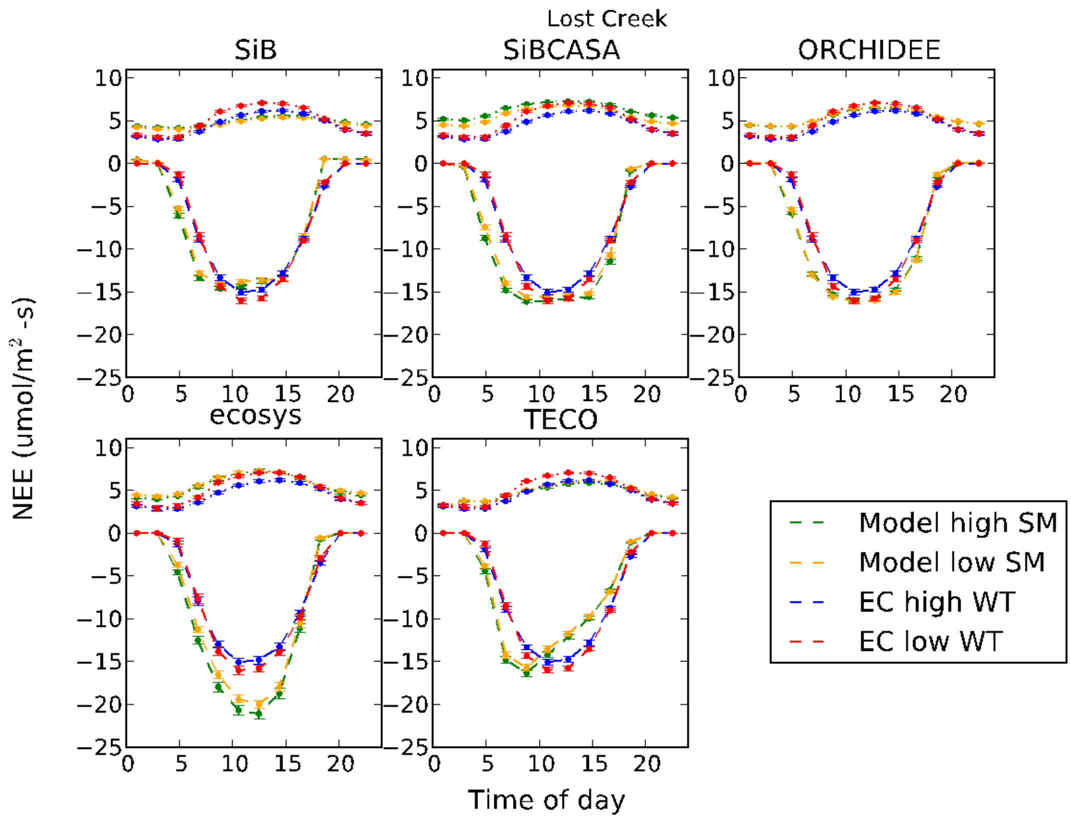
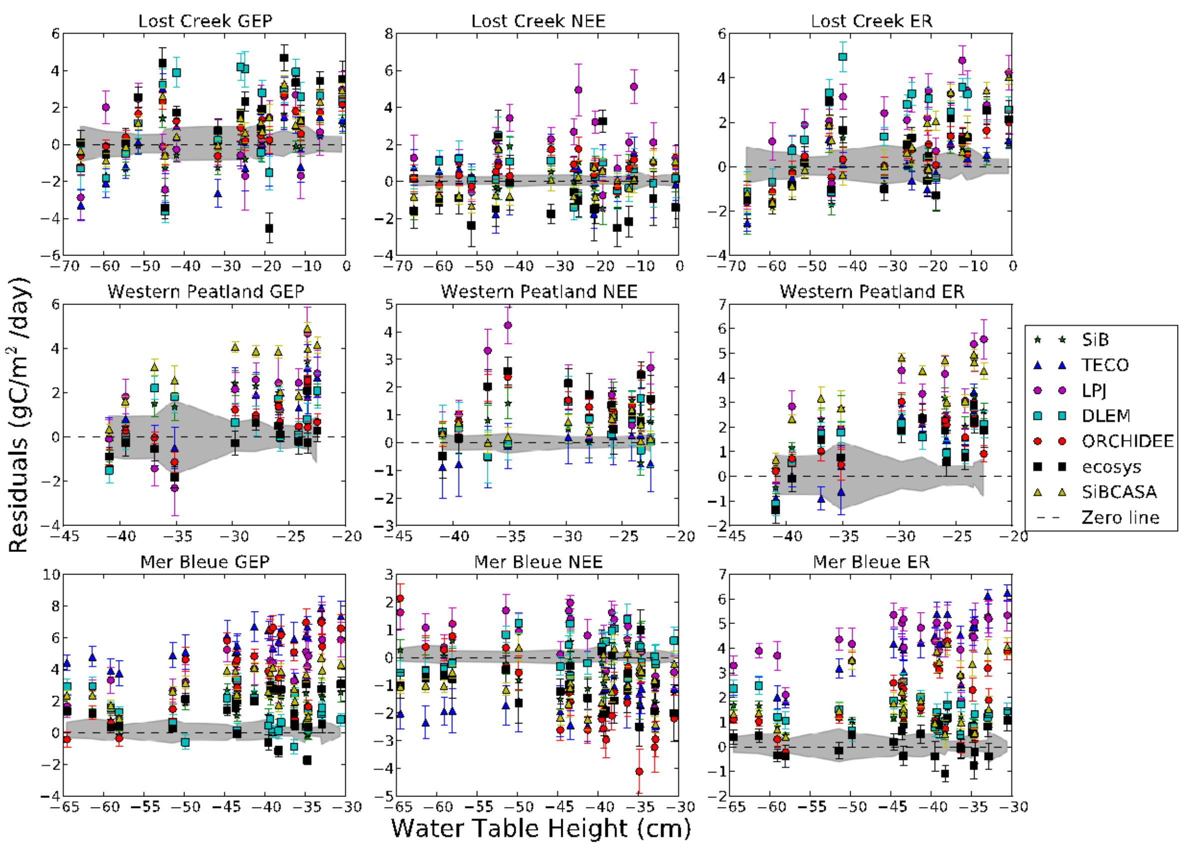


Figure 13. Model residuals for summer months. Residuals are shown for months of June, July, and August, plotted as a function of monthly mean observed water table level for each site. Residuals are defined as simulated minus observed fluxes. Left column is gross ecosystem production (GEP), middle column is net ecosystem exchange (NEE), and right column is ecosystem respiration (ER). Error bars on points indicate 95% confidence interval of monthly model mean. Gray region indicates 95% confidence interval of monthly mean observed fluxes. Relatively consistent model-data error is found across the three sites. Prediction error tends to increase with higher water table, especially for ecosystem respiration, and secondarily for gross primary production, leading to a net underestimate of NEE.



Research products

Project website: http://flux.aos.wisc.edu/twiki/bin/view/Main/LabResearchWetland Links on this page include our collaborative wiki where team members can present research results and upload meeting minutes.

Our data products page has been harmonized with the larger flux tower network and is now located at: http://flux.aos.wisc.edu/twiki/bin/view/Main/ChEASData

This page contains 30-minute computed fluxes, micrometeorological, biological, ecophysiological, and hydrological data for tall flux tower sites in the region, including the wetland towers supported or analyzed here. Access to powerpoint presentations and publications is also provided via the wiki. Flux tower data has also been sent to the ChEAS, Ameriflux, and Fluxnet teams for further quality assurance and archiving on their databases.

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Peer reviewed:

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Student Degrees Supported

Ruben Behnke, University of Wisconsin Atmospheric & Oceanic Sciences (M.S student), was supported for one year on this project. Ruben's M.S. thesis focused ib downscaling of climate change data from observation and model data. While his M.S. work focused on North America as a whole, for this project, he collected and analyzed climate trend data in Wisconsin and relationships to precipitation.

Nicole Schroeder, University of Wisconsin Atmospheric & Oceanic Sciences (B.S student), was supported as senior thesis student and a summer undergraduate intern. She led the NACP model-data synthesis for wetland carbon cycle and contributed to a manuscript of results based on her senior undergraduate thesis.

Benjamin Sulman, University of Wisconsin Atmospheric & Oceanic Sciences (M.S./Ph.D. student). Ben was supported by this grant for two years and completed his M.S. thesis "A comparison of carbon dioxide, water, and energy fluxes at a drying shrub wetland in northern Wisconsin, USA with nearby wetland and forest sites". His work has led to three first-author publications that have focused on the role of wetland carbon cycle-water table relationships and its implication for modeling. His Ph.D. work, supported by other grants has focused on regional upscaling and forest succession modeling. Ben has become well regarded in the carbon cycle community for his contributions to wetland carbon cycle model analysis.

Bhaskar Mitra, University at Buffalo Department of Geography (Ph.D., 2011). Bhaskar was a university Presidential Fellow and who was been partially supported (summer only) on this project. His work involved developing improved models of rhizosphere controls on respiration, focusing specifically on coupled belowground plant hydraulics and carbon cycling. His work has lead to some innovative additions to the TREES model involving explicit coupling of belowground processes and non-stomatal control of gross primary production. He graduated with his Ph.D. in 2011 and is now a post-doc with Shirley (Kurc) Papuga and Paul Brooks at the University of Arizona Critical Zone Observatory.

David Roberts, University at Buffalo Department of Geography (M.S. student). Dave completed coupling a mechanistic plant hydraulics model with the TREES model. This model will be used to parameterize a distributed model of ecosystem evolutionary dynamics to examine drought survival strategies and their effects on forest succession and carbon fluxes.

Taryn Tomasik, University at Buffalo Department of Geography (M.S. 2011). Taryn was support by the project in summers. Her M.S. thesis work focused on regional and inter-site variability in forest canopy processes, and specifically canopy stomatal conductance, which is relevant to the development of the TREES model used here.

Mary Freiss, SUNY Stony Brook (NSF REU). Mary spent the summer of 2010 in Dr. Mackay's lab working on NICCR-related research. Specifically, Mary worked on methods of adapting RHESSys, a fully transient and spatially distributed of hydrology, ecosystems, and biogeochemical cycling, to the wetland-rich landscape. RHESSys computes lateral groundwater flow fully coupled to the vertical processes, making it complementary to the TREES model. RHESSys was successfully adapted to the ChEAS site and Mary's work continues as part of Ryan Stotz's Masters work.

Ryan Stotz, University at Buffalo Department of Geography (M.S. student). Ryan continues to work on adapting RHESSys for the wetland-rich landscape.

Final Report: **How will productivity, evapotranspiration & insect herbivory of the Midwest agroecosystem respond to the combined drought and elevated [CO_2] anticipated for 2050?**

Abstract

At over 60 million hectares, the soybean (C_3)-maize (C_4) ecosystem is the largest single ecosystem type in the 48 states and dominates the Midwest. We have discovered how projected changes in precipitation and [CO_2] will affect ecosystem C-cycling and water fluxes. Key findings were: (1) contrary to current paradigm, growth of a model C_3 species at elevated CO_2 did not consistently reduce evapotranspiration and increase soil moisture; (2) stomatal sensitivity of a model C_3 species to soil moisture deficit was greater at elevated CO_2 compared to ambient [CO_2]; (3) growth of a model C_4 species at elevated [CO_2] reduced evapotranspiration, conserving soil moisture and ameliorating physiological stress, but did so with insufficient strength or frequency to enhance productivity; and (4) drought reduces susceptibility to herbivory in a model C_3 species grown under elevated CO_2 conditions. Collectively, these results indicate that elevated [CO_2] will ameliorate drought stress effects on both C_3 and C_4 components of the Midwest agroecosystem less than previously assumed.

Research Activities

Our objective was to reduce uncertainty about how future changes in precipitation and [CO_2] will affect ecosystem C-cycling and water fluxes, by testing the following hypotheses:

1) Increased drought stress will depress ET, GPP, NPP across the entire Midwest agroecosystem via reduced stomatal conductance (g_s), photosynthesis (*A*) and leaf sugar and N contents in C_3 (soybean) and C_4 (maize) crops.

2) Elevated [CO_2] will counteract drought effects in C_3 species via direct stimulation of *A*, accompanied by lower $g_{s,}$ which conserves soil moisture and indirectly stimulates *A*. These will be non-additive interactions.

3) Elevated [CO_2] will counteract drought effects in C_4 species *only* via lower $g_{s,}$ which conserves soil moisture and thereby indirectly stimulates *A*. This reflects an important difference between climate change effects on the two major components of the Midwest agroecosystem, which needs to be understood.

These questions were addressed with experimentation during the 2007-2011 growing seasons (including period of no-cost extension).Maize responses to drought and elevated CO_2 were assessed in 2008. Soybean responses to elevated CO_2 and water availability were assessed across all years, including deployment of rain-out shelters to impose a drought treatments in years 2009-2011. Below we report highlights of initial data analysis. Analysis of treatment effects on below-ground productivity, root-to-shoot-signaling, plant hydraulics and photosynthetic physiology are on-going.

Research highlights

Significant variation in the magnitude and direction of elevated CO_2 effects on evapotranspiration and soil moisture associated with C_3 plant stress responses to interannual variation in climate

A key assumption in projections of future food supply and ecosystem function is that elevated [CO_2], through reduced stomatal conductance (g_s), results in lower water use, conservation of soil moisture and amelioration of losses in productivity due to drought stress. The effects on soil $H_2O\%_{v/v}$ of growing soybean at elevated [CO_2] under field conditions were tested in a Free-Air CO_2 Enrichment (FACE) experiment located in Champaign, Illinois, U.S.A.. There were 4 plots at ambient [CO_2] (~385 µmol mol^{-1}) and 4 plots fumigated with CO_2 from shortly after planting until crop maturity in order to simulate conditions predicted for 2050 (~550 µmol mol^{-1}; Prentice et al 2001). Soil $H_2O\%_{v/v}$, midday g_s and leaf area index (LAI) have been measured and analysed over the

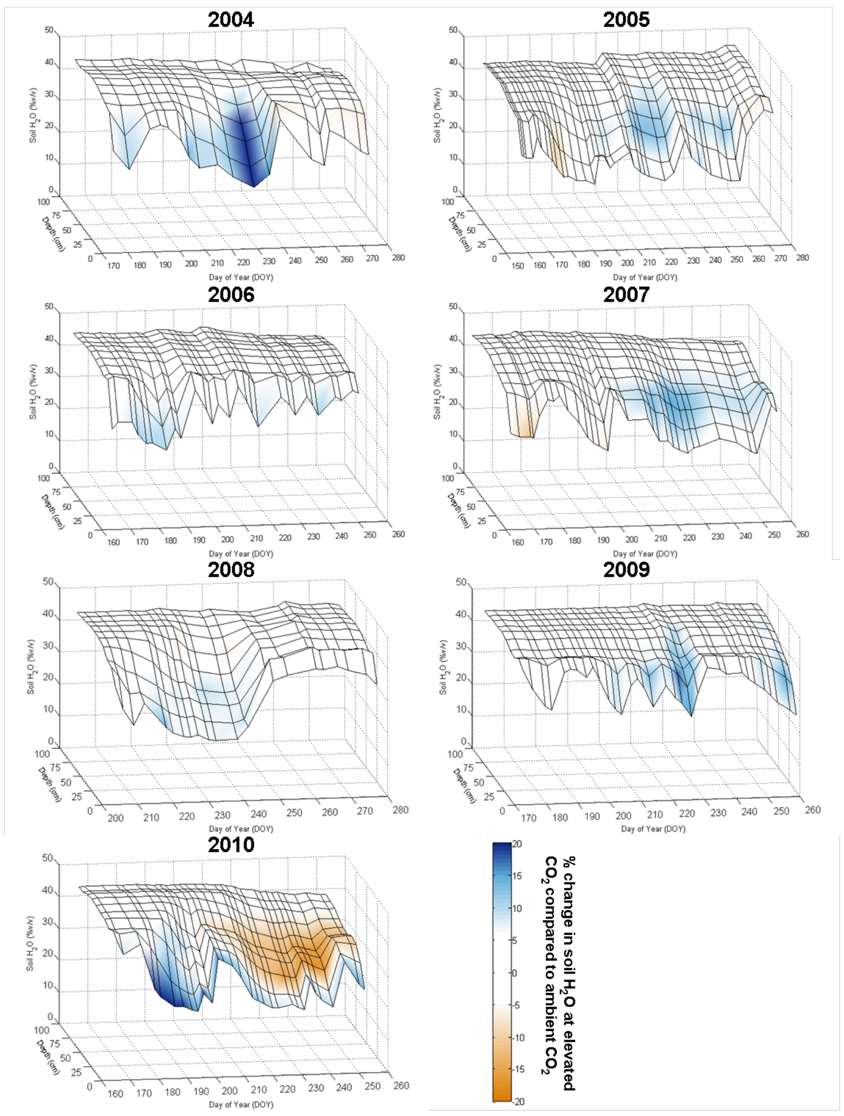

Fig. 1 Time course of volumetric water content ($H_2O\%_{v/v}$) for the soil profile of depths 5 – 105 cm in plots of soybean grown at ambient [CO_2] (3D mesh surface) during the growing seasons of 2004 – 2010. Color shading indicates the relative effect of elevated [CO_2] on $H_2O\%_{v/v}$. Each line parallel with the x-axis on the mesh surface represents the variation in $H_2O\%_{v/v}$ of a 10-cm layer of soil against day of year (DOY). Each line on the mesh surface going into the page represents the variation in $H_2O\%_{v/v}$ with depth in 10-cm increments on a specific DOY. The difference in $H_2O\%_{v/v}$ in plots of soybean grown at elevated [CO_2] relative to ambient [CO_2] (%) is represented by color shading of the 3D surface at the corresponding depth and DOY. Data are the treatment means of replicate plot values (n = 4).

course of 7 complete growing seasons for soybean. Soil $H_2O\%_{v/v}$ was measured every 3-5 days at 10-cm increments between depths of 5 cm to 105 cm. The potential to statistically resolve treatment effects was favoured by the high resolution and extent of the sampling (67,520 measurements of soil $H_2O\%_{v/v}$ during 29 drying events) along with the low genetic and environmental variability of the study system. In addition, utilization of FACE technology avoided the unwanted restriction of growth volume or perturbation of environmental conditions associated with other experimental approaches that can have equal or greater effects on soil $H_2O\%_{v/v}$ than elevated [CO_2]

Soil drying events occur when ET is greater than water inputs to the soil from precipitation. Greater $H_2O\%_{v/v}$ at elevated [CO_2] can result from lower g_s and, therefore, lower ET, causing soil water deficit during drying periods to accumulate more slowly. While this mechanism was observed to frequently operate, the experimental data was inconsistent with the current paradigm of how elevated [CO_2] improves soil moisture status in two important ways. First, when soil $H_2O\%_{v/v}$ was greater at elevated [CO_2], the effect was frequently limited to certain layers within the rooting profile, rather than the entire rooting profile (Fig 1). Second, plant growth at elevated [CO_2] did not consistently result in greater $H_2O\%_{v/v}$ when comparing drying events either within or between growing seasons. Unexpected responses were observed in three growing seasons (Fig 1). In the latter half of 2010, soil moisture was significantly lower at elevated CO_2, indicating greater not lower rates of evapotranspiration. This was associated with greater than average temperatures and plant stress that manifested itself in low LAI in ambient CO_2 plots. In 2008, the crop was stressed by a natural drought event leading to modest stress effect on LAI, with the end results that CO_2 had no effect on soil moisture. This response was reproduced in the drought treatments imposed using rainout shelters in 2009 and 2010.

The stimulation of *A* at elevated [CO_2] was diminished significantly when soil drying was equal or greater in elevated CO_2 compared to ambient [CO_2]. This suggests that increasing temperature and drought will diminish the benefits of elevated [CO_2] to plant productivity in the future more than currently predicted. This data uniquely demonstrates the importance of the 3-way interaction between elevated CO_2, temperature and water availability in determining plant and ecosystem function under future scenarios of altered climate.

Elevated CO_2 Increases Stomatal Sensitivity to Reduced Soil Moisture in Soybean

Atmospheric CO_2 and drought frequency/severity are expected to increase in the coming century. Elevated CO_2 is expected to ameliorate drought stress by reducing stomatal conductance (g_s), which is expected to conserve soil volumetric water content (VWC); and by increasing root biomass, which is expected to improve plant access to water. We tested this assumption at the soybean Free Air CO_2 Enrichment (soyFACE) facility in Champaign, IL, where soybean was grown under ambient CO_2 (aCO_2) or elevated CO_2 (eCO_2) in combination with control or reduced precipitation in 2009 and 2010. In 2009, lower soil VWC in the reduced precipitation treatment caused a 9% reduction in g_s and a 9% reduction in photosynthetic carbon assimilation (*A*) in aCO_2. Surprisingly, reduced precipitation caused similar reductions in soil VWC but greater reductions in g_s (20%) and *A* (15%) in eCO_2. In 2010, reduced precipitation caused a smaller reduction in soil VWC in eCO_2 compared to aCO_2, but equivalent reductions in g_s (21-22%) and *A* (13-16%) were observed in aCO_2 and eCO_2. Therefore, these two years of data are consistent with a mechanism where a given reduction in soil VWC drives greater reductions of g_s and *A* at eCO_2 compared to aCO_2. We hypothesize that, by increasing root length in shallow soil, eCO_2 increased exposure of soybean to dry soil, causing greater water deficit sensing and signaling. This mechanism is at odds with the widely held assumption that eCO_2 will consistently ameliorate drought stress, with implications for projections of future food security and targets for biotechnological improvement of soybean yield.

Impairment of C_4 photosynthesis by drought is exacerbated by limiting nitrogen and ameliorated by elevated [CO_2] in maize

Predictions of future ecosystem function and food supply from staple C_4 crops, such as maize, depend on elucidation of the mechanisms by which environmental change and growing conditions interact to determine future plant performance. To test the interactive effects of elevated [CO_2], drought and nitrogen (N) supply on net photosynthetic CO_2 uptake (*A*) in the world's most important C_4 crop, maize (*Zea mays*) was grown at ambient [CO_2] (~385ppm) and elevated [CO_2] (550ppm) with either high N supply (168 kg N ha^{-1} fertilizer) or limiting N (no fertilizer) at a site in the U.S. Corn Belt. A mid-season drought was not sufficiently severe to reduce NPP, but caused significant physiological stress, with reductions in: stomatal conductance (up to 57 %), *A* (up to 44 %) and the *in vivo* capacity of phosphoenolpyruvate carboxylase (up to 58 %). There was no stimulation of *A* by elevated [CO_2] when water availability was high, irrespective of N availability. Elevated [CO_2] delayed and relieved both stomatal and non-stomatal limitations to *A* during the drought (Fig 2). Limiting N supply exacerbated stomatal and non-stomatal limitation to *A* during drought. However, the effects of limiting N and elevated [CO_2] were additive, so amelioration of stress by elevated [CO_2] did not differ in magnitude between high N and limiting N supply. These findings provide new understanding of the limitations to C_4 productivity that will occur under future field conditions of the largest C_4 agroecosystem in the world.

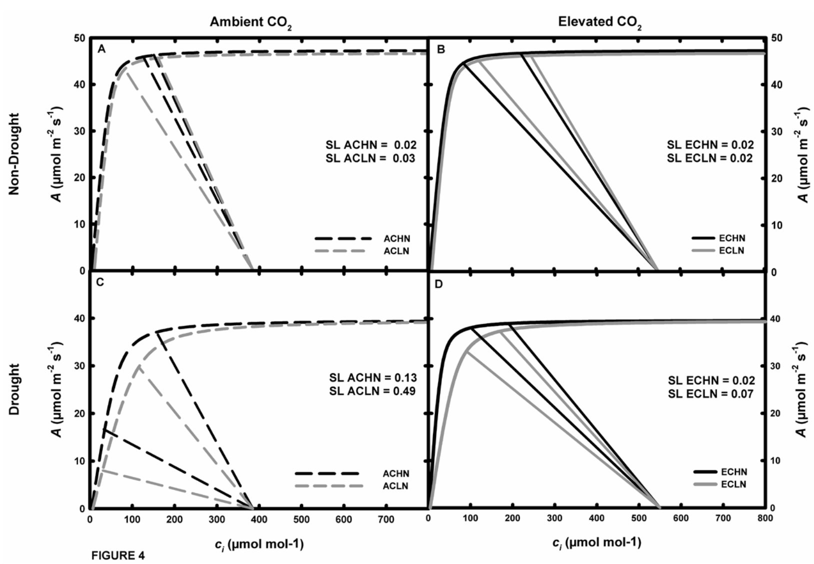

Figure 2. Summary of A/c_i response curves and CO_2 supply functions for maize grown at ambient [CO_2] (Panels A and C, dashed lines) and elevated [CO_2] (Panels B and D, solid lines) as well as high N (black lines) and limiting N (grey lines) during non-drought conditions (panels A and B) or drought conditions (panels C and D). A/c_i response curves represent statistically significant treatment effects for values of V_{pmax} and V_{max} (n = 4) under non-drought conditions and drought conditions. Superimposed are supply functions representing the maximum and minimum of c_i observed at midday in the field under non-drought conditions and drought conditions. Estimates of stomatal limitation (SL) using mean midday c_i in each treatment are reported in each panel.

Drought reduces susceptibility to herbivory in Glycine max grown under elevated CO_2 conditions

To investigate the combined effects of elevated CO_2 and drought on plant-insect interactions, transcripts and metabolites in three major hormone signaling pathways (jasmonic acid [JA], salicylic acid [SA], ethylene [ET]) and related defenses in soybean (*Glycine max*) were examined after Japanese beetle (*Popillia japonica*) feeding. Nutritional quality and Japanese beetle preference for tissue grown under elevated CO_2 and drought also were determined. Elevated CO_2 increased the concentration of leaf sugars and dampened JA/ET signaling, but increased the abundance of SA compared to plants grown in ambient CO_2. Exposure to drought had no effect on leaf sugars but stimulated the induction of transcripts related to JA/ET biosynthesis. When applied in combination, the impacts of elevated CO_2 were reduced for transcripts related to JA and ET accumulation. Exposure to elevated CO_2 alone increased susceptibility of soybean to beetle damage. However, exposure to elevated CO_2 and drought together negated the impact of elevated CO_2 in isolation, removing the increased susceptibility. This research highlights the importance of examining interactions among the major components of global change under field conditions.

Publications

RJC Markelz, RS Strellner, ADB Leakey (2011) Impairment of C_4 photosynthesis by drought is exacerbated by limiting nitrogen and ameliorated by elevated [CO_2] in maize. *Journal of Experimental Botany* 62(9): 3235-3246.

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In prep:
SB Gray, RJC Markelz, JM McGrath, O Dermody, DR Ort, ADB Leakey Should the paradigm of wetter soils in an elevated-[CO_2] world be hung out to dry? for *Nature Climate Change*

Student degrees supported
Clare Casteel (Ph.D. 2011)
Sharon Gray (Ph. D. in progress)
Cody Markelz (Ph. D. in progress)

Final Report – December 22, 2011
Midwestern Regional Center of the Department of Energy's
National Institute for Climatic Change Research (NICCR)

Impacts of Historical and Future Changes in Climate and Atmospheric CO_2 on Terrestrial Ecosystem Structure and Functioning in the Midwestern U.S.

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1. Abstract

The overall objective of this project is to use a Dynamic Global Vegetation Model (DGVM; Agro-IBIS) – which includes a detailed representation of agroecosystems – to understand how past and anticipated future changes (1948-2100) in agricultural land management, climate, and atmospheric CO_2 have affected and will affect ecosystem structure and functioning in the Midwest NICCR region. We focus, in particular, on regional-scale carbon, water, and energy cycling. Major steps that have been completed for the project include: (1) testing Agro-IBIS at two agricultural sites as part of the AmeriFlux network (Bondville, IL and Rosemount, MN), as well as a wetland site in southwestern Nebraska; (2) creating and validating a new, high resolution (~10-km) gridded daily climate dataset across the U.S.; (3) modifying Agro-IBIS to incorporate new high-resolution climate, soils, and vegetation datasets; and (4) completing a series of simulations to study the historical impacts of climate change on natural and managed ecosystems since the late 1940s, including changes in carbon, water, and energy cycling.

2. Research Activities

Our overall objective is to use Agro-IBIS to understand how past and anticipated future changes (1948-2100) in agricultural land management, climate, and atmospheric CO_2 have affected and will affect ecosystem structure and functioning in the Midwest NICCR region. The goals are to quantify changes in regional-scale carbon, water, and energy cycling, highlighting the availability of ecosystem goods and services (e.g., crop yields, forest/grassland productivity, and freshwater availability). We constructed simulations of the recent past (1948-2007) to examine how changes in climate, atmospheric CO_2, and agricultural management have impacted ecosystem structure and functioning, and carbon, water, and energy exchange. While our model has been tested extensively across the U.S. under previous DOE NIGEC/NICCR support, we performed additional validation of historical simulations of carbon, water, and energy exchange to increase model confidence of both historical and future simulations. Our proposed work focused on these key objectives:

1) Incorporate ~10-km spatial resolution Agro-IBIS model driver datasets (land cover and daily climate) for 1948-2007 and create new scenarios of future climate and atmospheric CO_2 for 2008-2100 using regional assessment data and GCM output from the IPCC Fourth Assessment Report (AR4). We will use several observational datasets (e.g., MODIS, AmeriFlux, SoyFACE, soil moisture) to validate model processes and output.
2) Investigate how historical changes in climate (temperature and precipitation), cropland management (planting dates and hybrids, nitrogen fertilizer, irrigation, and reduced tillage practices), and atmospheric CO_2 have impacted potential vegetation distribution, carbon cycling (crop yields, forest NPP), water cycling (soil moisture, evapotranspiration, runoff), and energy exchange (sensible, latent, and soil heat fluxes) across the Midwest USA.

Summary of activities

- We validated a 60-year, high-resolution climate dataset provided by ZedX, Inc. through comparison with other observations, as well as calculation of climatologies, trends, etc. During this validation process, we observed problems with the incoming solar radiation values, which ZedX obtained from reanalyses rather than surface observations (due to data sparseness and inaccuracies). Problems included unrealistic temporal and spatial variability (in the case of the NCEP/NCAR reanalysis) and a high bias (in the case of both the NCEP/NCAR reanalysis and the North American Regional Reanalysis). Comparisons with the GEWEX SRB dataset and theoretical clear sky values have been used to rectify this problem.

- Agro-IBIS model simulations at several AmeriFlux crop sites (Bondville, IL and Mead, NE) were undertaken to support a cross-model comparison for the North American Carbon Program (NACP). This work is part of a series of publications related to NACP.

- Agro-IBIS has been run at an additional validation site for a wetland in southwestern Nebraska. Model output has been compared with water and energy balance parameters collected at the site (e.g., evapotranspiration, albedo, sensible heat flux, etc.). This site has revealed the need to explicitly account for groundwater in Agro-IBIS, and a variety of algorithms were tested to represent groundwater (of varying complexity – from imposed saturation in known wetland areas to fully coupled groundwater models). We have now completed model simulations both with and without imposed groundwater levels, and the model simulations (with groundwater) compare very favorably with the wetland observations. These results have now been incorporated into regional-scale simulations to examine the impacts of climate variability on the Upper Midwest.

- We incorporated a fire disturbance routine to the Agro-IBIS model. Two methods of simulating periodic burning of natural vegetation burning have been implemented: (1) ‘condition-based’ burning, which burns according to soil moisture, fuel load, and individual plant functional type fire resistance, and (2) ‘intervallic burning’, which burns a set percentage of forest/grassland biomass at regular time intervals. Our model results suggest that the addition of fire is crucial in simulating a realistic pattern of potential vegetation across the Upper Midwest NICCR region with Agro-IBIS.

- We have continued to examine and document trends in agricultural land management across the Midwest US from analyses of USDA crop progress data, and incorporated these new datasets into Agro-IBIS simulations.

- High-resolution model simulations from 1948-2007 across the Upper Midwest USA revealed the impacts of recent climate change on NPP trends/changes, as well as changes in the components of the water budget across the region.

3. Research Highlights

A. Incorporating the role of disturbance/fire in dynamic vegetation modeling

Disturbances such as fire and wind play an important role in determining the nature of vegetation within many ecosystems. It is believed that inclusion of fire and other kinds of disturbance in vegetation modeling is necessary to simulate vegetation dynamics correctly in all dynamic vegetation models. An optimal goal that we have set for the fire/disturbance model is for it to generate deciduous forests in the southern portion of the region and evergreen forests in the north. As part of graduate student Melissa Motew’s MS thesis (supported by this NICCR grant), we successfully accomplished that goal in 2011.

B. Examining trends in agricultural land management across the Midwest U.S. and investigating the impact of carbon, water, and energy exchange.

Documenting land management trends for corn and soybeans from USDA crop progress data. Planting date affects corn and soybean yields, partly by modifying the length of the vegetative and reproductive growth periods. We have investigated state-level trends in planting date, start of the reproductive period (R1), and maturity date for corn and soybeans across the Midwest U.S. NICCR region (see **Figure 1** as an example; Sacks and Kucharik, 2011). These dates were determined by finding 50% completion of the relevant stage in interpolated weekly USDA crop progress reports. Averaged across the U.S., corn planting dates advanced 2.7 days per decade between 1981 and 2009, and soybean planting dates 3.8 days per decade. For both crops, this shift to earlier planting was accompanied by lengthening of the growth period.

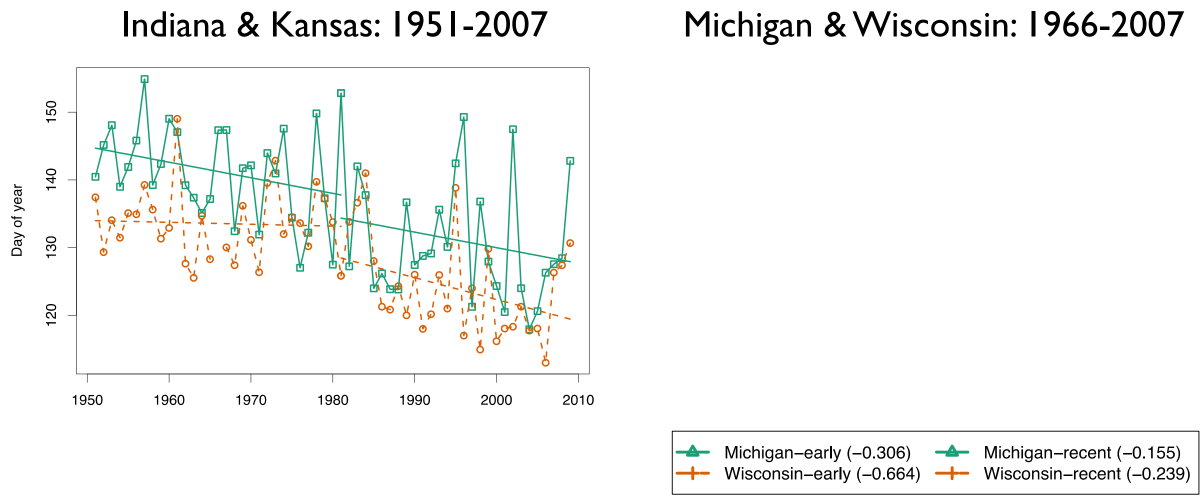
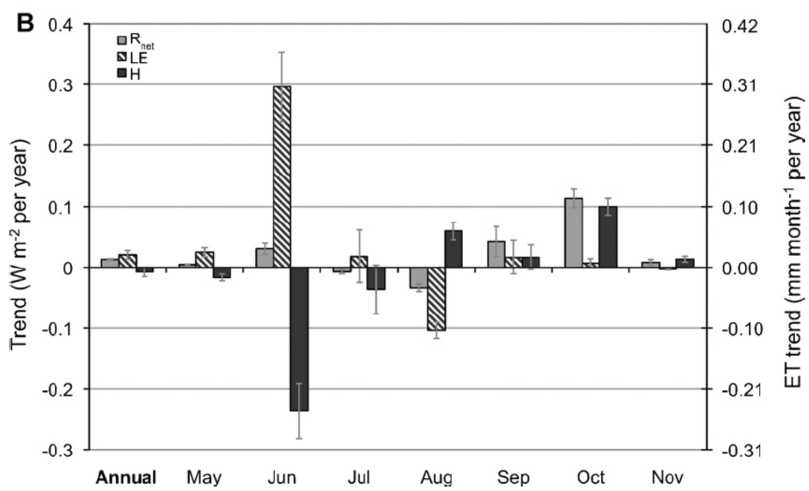


Figure 1: Long-term trends in corn planting date across the Midwest US. Significant variability exists from state to state, highlighting the necessity to collect additional data on land management trends to drive ecosystem models and better understand the impacts on spatial and temporal changes in coupled carbon, water, and energy balance.

These new land management data were used as drivers in the Agro-IBIS model. By knowing specifically how agricultural management has been changing across the Midwest since the mid 1970s, we can separate the relative contributions of land use change vs. climate change and their respective impacts on trends in NPP, crop yields, as well as carbon cycling, evapotranspiration, and energy balance (**Figure 2**; Sacks and Kucharik, 2011).

Figure 2 (from Sacks and Kucharik, 2011): Effects of changes in corn planting dates and cultivars on modeled Rnet, LE and H. Bars show linear trends (1981–2005) of the regionally averaged differences between the model runs accounting for changes in cultivars and planting dates and the CONTROL run (static cultivars/planting dates), for the annual average and selected monthly averages. (For months not shown, differences were small.) Error bars show 95% confidence intervals. The right-hand axes translate the LE values into evapotranspiration (ET) units. Averages are given over corn-growing croplands—not the region's total area.



C. Simulating trends in NPP and water balance across the Upper Midwest USA.

We investigated the impacts of recent climate change over the 1948-2007 period on potential vegetation of the Upper Midwest U.S. We drove Agro-IBIS using the ZedX climate data set consisting of daily meteorological measurements at a spatial resolution of 5 minutes x 5 minutes (~8km x 8km). We observed total increases in grid cell values of NPP generally ranging from 20–150 g C m^{-2} (**Figure 3A**), based on linear trend analysis. We determined the influential role of increased summer relative humidity, increased annual precipitation and decreased mean maximum summer temperatures in driving these positive trends, likely through the alleviation of soil moisture and heat stress. We also observed a total increase in drainage throughout the region on the order of 20-140 mm yr-1 throughout the study period, driven primarily by increases in annual precipitation. Evapotranspiration had a highly varied spatial response over the 60-year period, with total change over the study period ranging between -100 and +100 mm yr^{-1} (**Figure 3B**). We also considered changes at the biome level, yet found the model to underperform in terms of capturing competitive interactions among plant functional types. A separate data analysis of the bioclimatic envelopes for plant functional types common to the region revealed no change to the boreal conifer tree climatic domain over the study period, yet did reveal a slightly expanded domain for the temperate deciduous broadleaf tree. The location of the Tension Zone, the broad ecotone dividing mixed forests in the north and southern hardwood forests and prairies in the south, was not observed to shift in either the data analysis or during the model simulation.

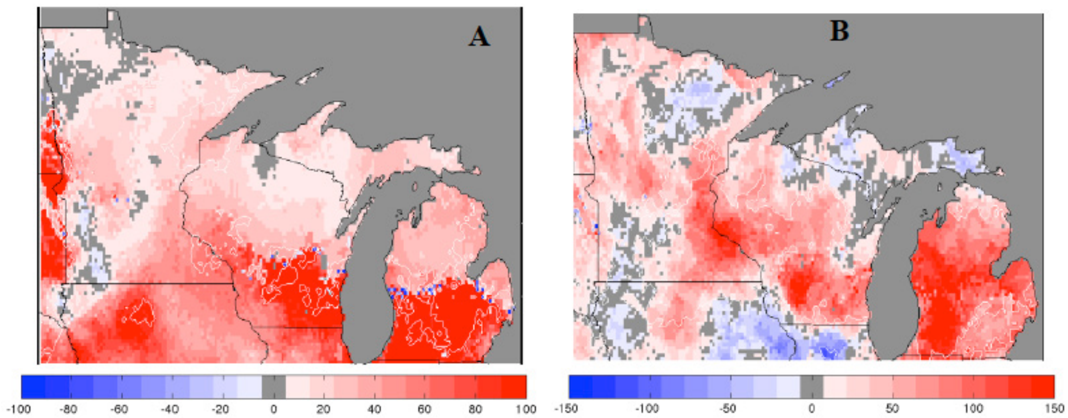


Figure 3 (from Motew and Kucharik, *in prep*): (A) trends in total NPP (g C m^{-2}), and (B) evapotranspiration (mm yr^{-1}) from 1948-2007.

D. Impacts of groundwater and interannual climate variability on the regional water balance

Comparison of Agro-IBIS simulations with evapotranspiration (ET) data collected at a validation site in southwestern Nebraska revealed the need to incorporate groundwater in Agro-IBIS (Figure 4), particularly in riparian zones and other wetland areas that exist throughout the Upper Midwest. Model tests that included an imposed depth-to-groundwater showed significantly improved simulations of ET and soil moisture. Additional tests were performed by running Agro-IBIS across the entire Upper Midwest with varying groundwater levels. The results showed that groundwater can have a significant impact on the surface energy and water balance, and we have used “depth-to-water-table” as an additional forcing variable when considering impacts on the regional energy and water balance.

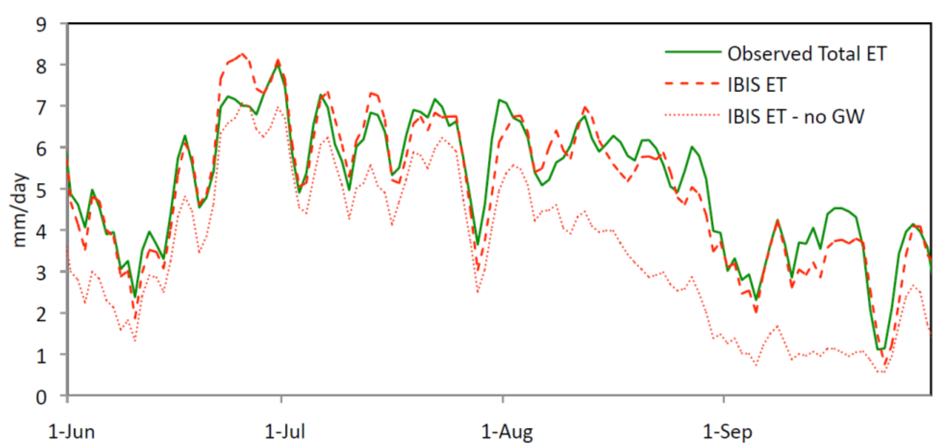


Figure 4. Comparison of observed and Agro-IBIS modeled ET (with and without groundwater) at a wetland field site in Nebraska during the 2009 growing season.

In addition to the incorporation of groundwater, regional model simulations were completed to investigate the effects of interannual climate variability on the energy and water balance of the central Plains region (particularly ET). This was accomplished by examining the observed co-variation in summer-mean atmospheric forcing across the 60-year historical record – specifically precipitation, solar radiation, maximum and minimum air temperature, and relative humidity. The observed covariance was used to generate realistic scenarios of "wet" and "dry" summer conditions (i.e., accounting for concomitant changes in precipitation, cloud cover, temperature, and humidity). We then used Agro-IBIS and the wet/dry scenarios to simulate the impact of interannual variations in summer climate on the water balance of the central Plains region. An example of the results is shown in Figure 5, which illustrates the effect on summer ET rates for two different vegetation types (natural vegetation and *Phragmites australis* – a water-intensive invasive plant that is prevalent in the region). As would be expected, the results show a significant drop in ET during dry summers, due to the decrease in available water (and despite coinciding increases in available energy – i.e., solar radiation). Interestingly, however, the response is more complex during wet summers (Figures 5a and 5b). In this scenario, ET is observed to increase in water-limited areas of the domain (primarily the western region), but decrease in eastern portions of the domain. This inverse response in ET reflects the more "energy-limited" nature of the eastern domain, where reductions in cloud cover dominate the impacts of increased precipitation.

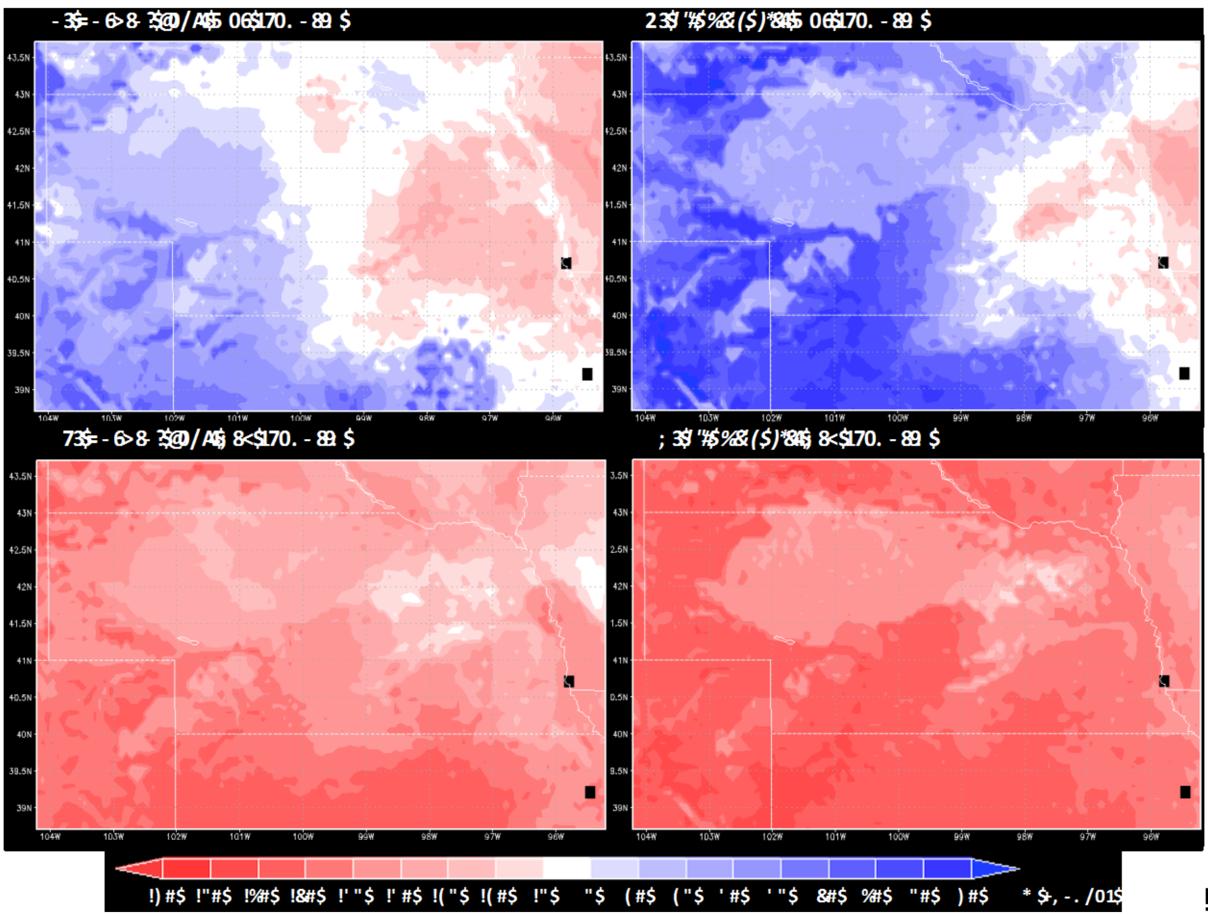


Figure 5. Percent change in modeled summer-mean evapotranspiration rates in response to a factor-of-1.5 increase ("wet scenario") and decrease ("dry scenario") in precipitation (as well as co-variations in solar radiation, air temperature, and relative humidity). Results are shown for both "natural vegetation" (left-hand column) and *P. australis* vegetation (right-hand column).

E. Enhanced Collaboration

We have held five Agro-IBIS modeling workshops during 2009-2011 in Madison WI, Ames IA, Lincoln NE, and Minneapolis MN. These workshops brought together graduate students, postdocs, and NICCR PIs from the University of Wisconsin-Madison (Kucharik), the University of Nebraska-Lincoln (Lenters), the University of Minnesota (Tracy Twine), as well as new collaborators from Iowa State University (Gene Takle and Brian Hornbuckle) and the University of Illinois (Andy VanLoocke). The purpose of these workshops was to: 1) discuss modeling developments, 2) describe new scientific approaches, and 3) work on research questions related to our respective NICCR grants. Agro-IBIS is now being used by our collaborators at Iowa State University, as they are interested in coupling Agro-IBIS to a regional climate model such as WRF or RegCM3. Agro-IBIS is also being used at the University of Illinois to investigate the impacts of Miscanthus and switchgrass on water balance across the Midwest USA. We have found these Agro-IBIS workshops to be extremely valuable for sharing ideas, model code, analysis techniques, and research results (particularly for the graduate students that we are training). As such, we are planning additional workshops, with the next one to be held in the spring of 2012 at Iowa State University.

4. Research Products

- A global version of the IBIS model continues to be made available at the University of Wisconsin Center for Sustainability and the Global Environment website to outside investigators who wish to check previous published results: http://www.sage.wisc.edu/download/IBIS/ibis.html
- State level data on corn and soybean planting date, silking/flowering, maturity, and harvest from 1979-2009 are available across the majority of the Midwest.
- We have completed the analysis and "calibration" of the solar radiation dataset provided by ZedX and have incorporated these improvements to the continental-scale, 5-minute daily climate dataset from 1948-2007. More specifically, the strong bias in the ZedX radiation dataset was removed by doing a gridcell-by-gridcell regression with the NASA GEWEX SRB 1.0-degree radiation dataset (from 1984-2007), which is a common reference dataset used for providing more robust estimates of spatially distributed incoming solar radiation. We expect this new product to provide improved simulations of the regional energy and water balance, and we are also using the radiation dataset to examine the impacts of historical cloud cover trends on ET, soil moisture, and runoff.

5. Publications (2008-2012)

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Twine, T.E., and **C.J. Kucharik**, 2008. Evaluating a terrestrial ecosystem model with satellite information of greenness. *Journal of Geophysical Research-Biogeosciences,* 113, G03027, doi:10.1029/2007JG000599.

6. Student Degrees Supported

Bo Dong, M.S. Candidate at University of Nebraska-Lincoln (Adviser: Lenters); Anticipated degree completion: August, 2012.

Melissa Motew, M.S. in Environment and Resources, The Nelson Institute for Environmental Studies, UW-Madison (Adviser: Kucharik); Degree conferral: August, 2011.

Phillip Mykleby, M.S. Candidate at University of Nebraska-Lincoln (Adviser: Lenters); Anticipated degree completion: May, 2012.

Evren Soylu, Ph.D. in Natural Resource Sciences, School of Natural Resources, University of Nebraska-Lincoln (Adviser: Lenters); Degree conferral: August, 2011.

Experimental and Modeling Study of Interactive Effects of Warming and Altered Precipitation on a Tallgrass Prairie in the Southern Great Plains

Drs. Yiqi Luo and Rebecca Sherry

Final Report, December 2011

Midwestern Regional Center of the Department of Energy's National Institute for Climatic Change Research

1. Abstract

After collecting two full years of treatment data on a field experiment designed to quantify the main and interactive effects of warming, harvesting, and altered precipitation regime on ecosystem processes and community structure, we have found important differences when comparing ecosystem respiration and transpiration from this site, which is dominated by C_3 photosynthesis species, to another of our experimental warming experiments, which is dominated by C_4 photosynthesis species, indicating that species composition has significant effects on carbon and water processes.

Warming interacted with halved precipitation to decrease C_3 and overall plant production. Our modeling analyses indicated that no three-factor interactions were substantial for evapotranspiration, net ecosystem gas exchange, ecosystem respiration, soil respiration, and water use efficiency. However, these effects were not consistent among various ecosystems; and because our latest field data do indicate significant 2- and 3-way interactions on plant productivity, more field and modeling studies are necessary to determine which interactions tend to be significant for which ecosystems.

2. Research activities

The overall objectives of this project were to: (1) to quantify main vs. interactive effects of experimental warming, added and reduced precipitation on ecosystem processes and community structure and (2) to integrate experimental results into models to improve our ability of predicting ecosystem responses to warming and altered precipitation.

We have now collected a full two years of treatment data and samples (the first year was spent building the experimental infrastructure and gather pre-treatment data) from a facility consisting of twenty-four 3x2 m plots, four replicates of each of six treatments (control, +3^{o}C warming, doubled precipitation, halved precipitation, warming plus double precipitation, and warming plus halved precipitation). Each plot is covered by a rainout shelter (if a halved precipitation plot) or a "dummy" rainout shelter (if not a halved precipitation plot). A water catchment sits next to each doubled precipitation plot (Fig. 1). With additional funding from Oklahoma Bioenergy Center, each plot includes two subplots, one for clipping to mimic biofuel feedstock harvest and one without clipping. The soil in each subplot is surrounded by 6ml plastic sheeting to a depth of 120 cm to

Fig. 1. Rain-out shelters and water catchments at the experimental site.

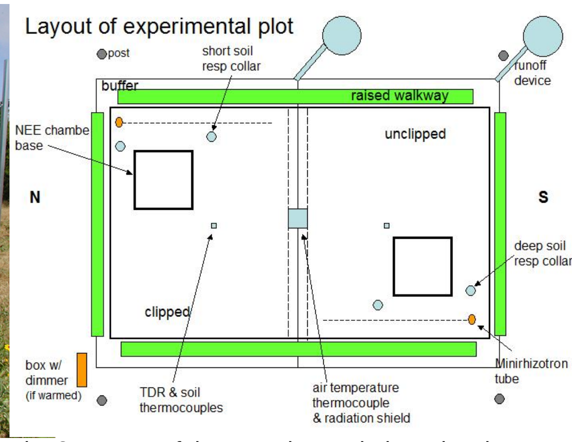

Fig. 2. Layout of the experimental plots showing placement of instrumentation. Resp = respiration.

prevent lateral soil water movement from interfering with treatment effects on soil moisture. Each subplot also contains soil temperature thermocouples at four different depths, a TDR probe to measure soil moisture down to 120cm depth, and a six-foot minirhizotron tube to visualize root growth (Fig. 2).

Data collected include: soil and air temperature, soil moisture at different depths, above-ground plant productivity (ANPP), root productivity, root growth, ecosystem evapotranspiration (ET), net ecosystem gas exchange (NEE), ecosystem respiration, ecosystem water use efficiency (WUE), auto- and hetero-trophic soil respiration, soil bulk density, soil C and N, plant species composition, canopy cover. Meanwhile, we have conducted modeling analysis on interactive effects of climate warming, altered precipitation, and elevated CO_2 on ecosystem carbon water processes such as net primary production (NPP), heterotrophic respiration (Rh), net ecosystem production (NEP), transpiration, and runoff.

3. Research highlights

We continue to analyze the numerical data (one portion of which has been submitted to Nature Climate Change), while some soil, plant, and root samples

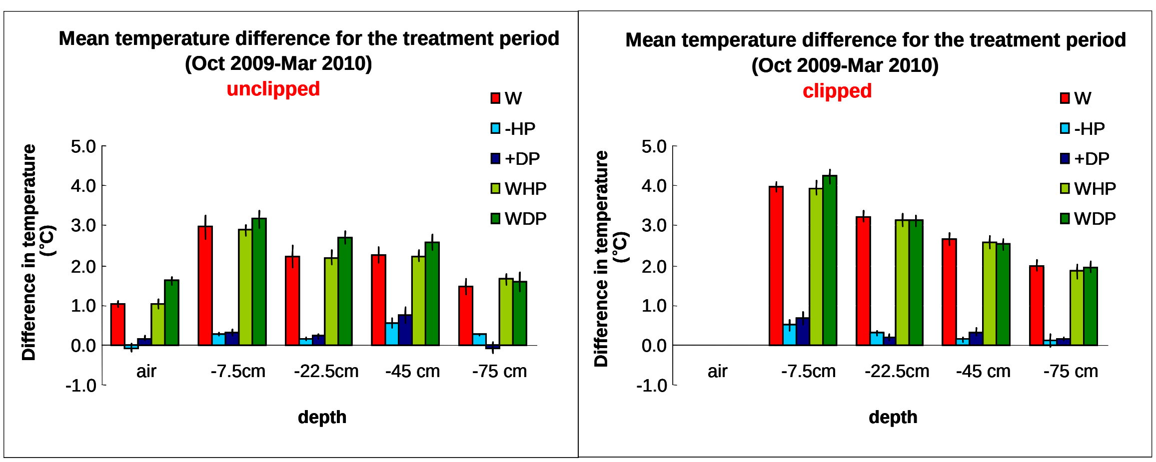

Fig. 3. Differences in air and soil temperature between each of the five treatments and the control. W = warmed, HP=halved precipitation, DP=doubled precipitation, WHP=warmed and HP, WDP=warmed plus DP.

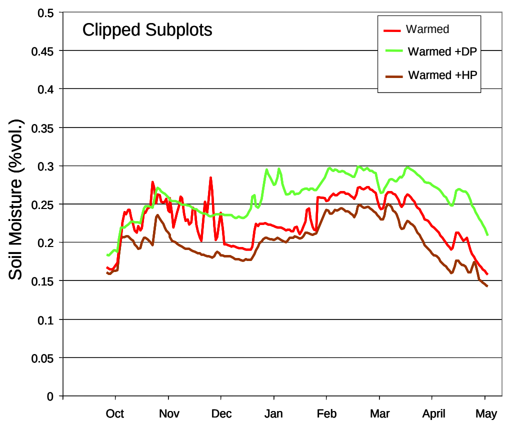

Fig. 4. Soil moisture in three treatments averaged from 0 to 120 cm depth.

will be processed in the coming year.

The radiant infrared heaters are performing as expected, reaching a target warming of +3^{o}C in the uppermost layer of soil (Fig. 3). Likewise, precipitation manipulation devices also perform as expected (example in Fig. 4).

In the first treatment year, plant productivity (above-ground biomass, AGB) was reduced only by

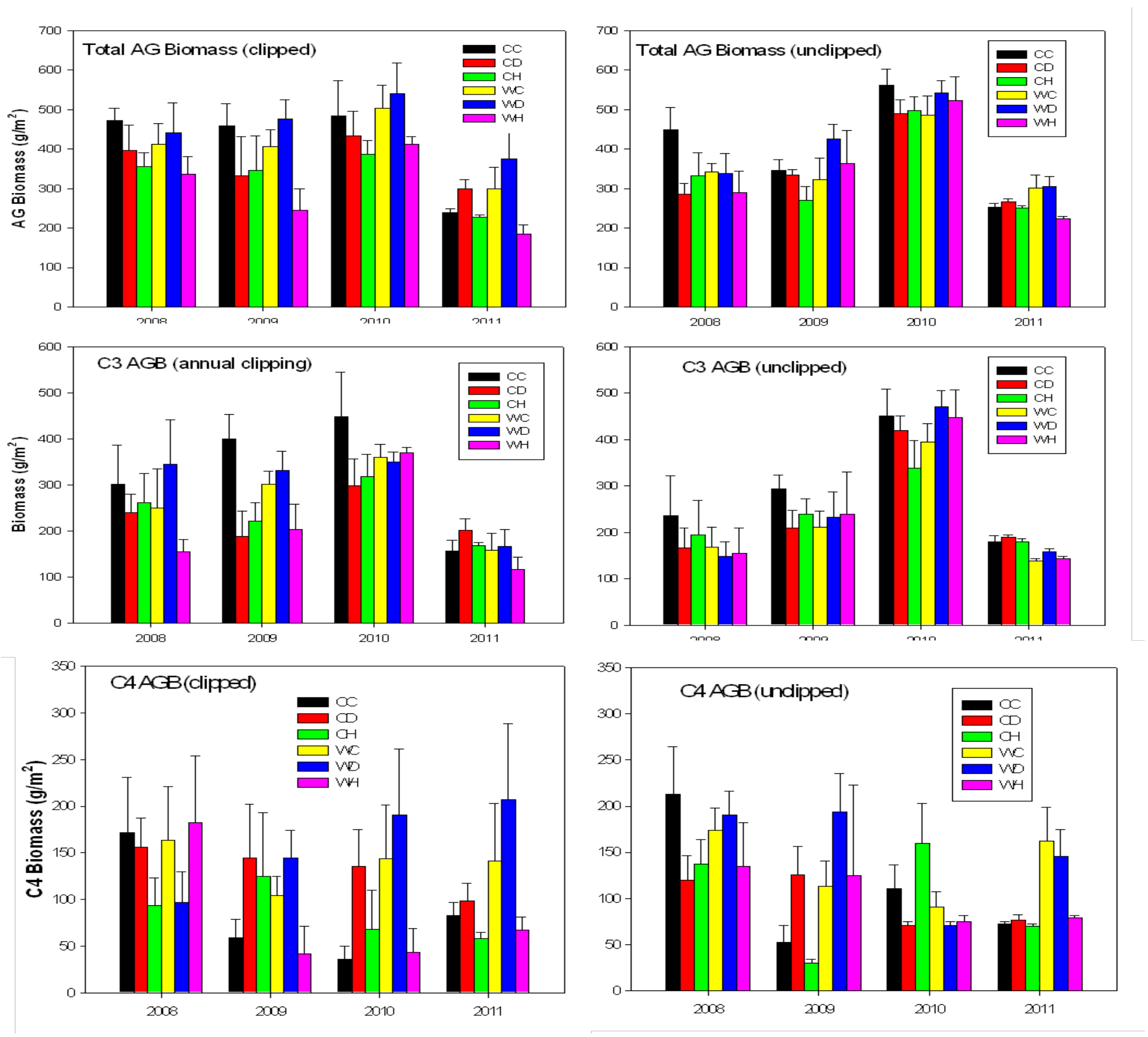

Fig. 5. Above-ground plant production for 2011 divided into C_3, C_4 and total components. C = control, HP=halved precipitation, DP= double precipitation.

the warming plus halved precipitation treatment, and this effect was due to significant effects of each of those treatments on C_3 plant biomass, not on C_4 plant biomass (not shown). However, in the second treatment year, warming and double precipitation both increased AGB as single factors, while those two factors together had an even greater positive effect on AGB (Fig. 5). Warming combined with halved precipitation decreased total AGB in clipped subplots but only C_3 AGB in unclipped subplots. Double precipitation alone increased both C_3 and C_4 AGB, but halved precipitation decreased only C_3 AGB, not C_4.

In 2010, harvesting of biomass reduced net ecosystem C exchange (NEE) while increasing ecosystem respiration (ER), evapotranspiration (ET), and gross primary productivity (GPP) (Fig. 6). Warming reduced ER and ET. The precipitation treatments had no significant effects during this time frame. Water use efficiency was de-creased by harvesting but increased by warming, the only physiological parameter to show any interaction between factors.

During the second year, NEE and results from this C_3-dominated site were compared to another warming experiment dominated by C_4 plants. Warming significantly decreased both GPP and ER but increased NEE (more net C uptake) in the C_3-dominated grassland. In the C_4-dominated grassland, warming significantly increased ecosystem respiration (ER), slightly increased gross primary productivity (GPP) and decreased net ecosystem exchange (NEE, less net C uptake) in 2009-2011. The different warming effects between the two

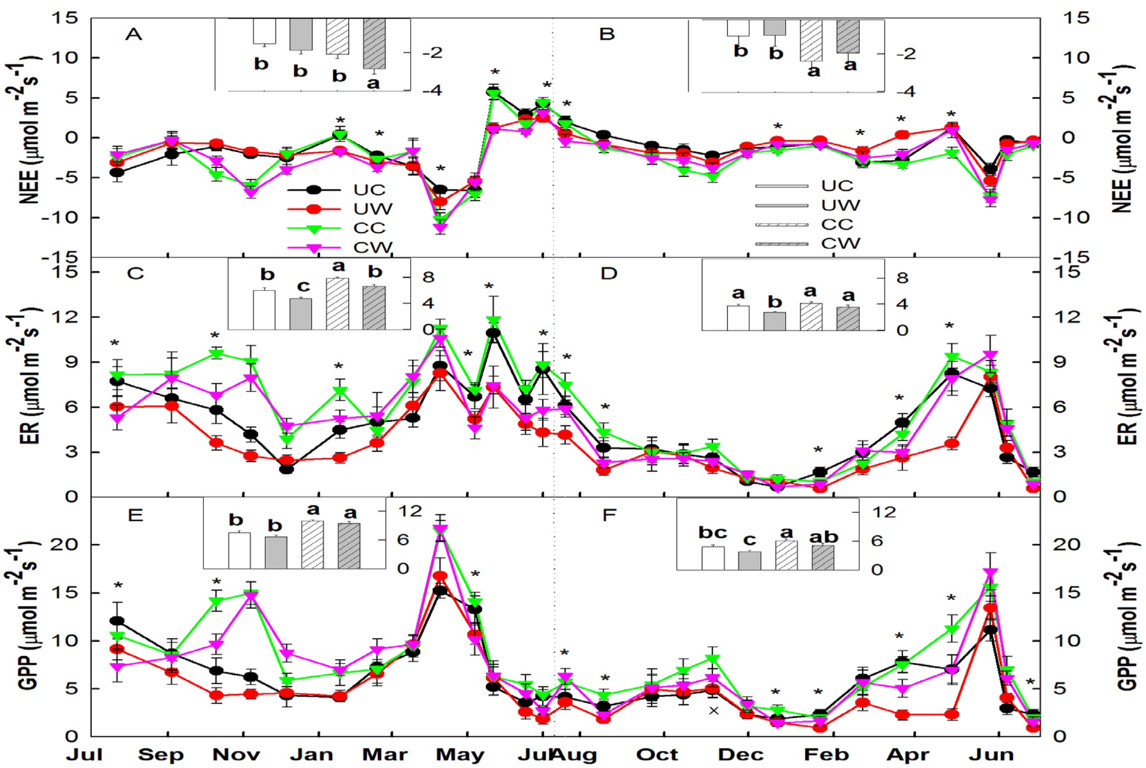

Figure 6. Seasonal dynamics and mean values of net ecosystem carbon exchange (NEE, A, B), ecosystem respiration (ER, C, D), gross primary productivity (GPP, E, F), and their response to climate warming during 2010 and 2011. The * above the curves indicates significant warming effects. The insets are the means of carbon fluxes across the seasons. Different letters in insets indicate significant difference ($P < 0.05$) in seasonal averages among treatments. UC = unclipped control, UW = unclipped warmed, CC = clipped control, CW = clipped warmed.

communities were partly due to a much lower optimum temperature of carbon fluxes in the C_3 than the C_4 vegetation. Across the plots at the two sites, warming-induced changes in NEE, GPP and ER were correlated positively with C_4 biomass proportion but negatively with C_3 biomass proportion, indicating that C_3 and C_4 composition determines warming effects on ecosystem carbon fluxes, highlighting the importance of species composition in modifying ecosystem response to climate change.

Measurements of soil respiration indicate that there is clear seasonal and interannual variation for both soil respiration (SR) and heterotrophic respiration (HR) (Fig. 7). There was a significant effect of clipping on SR, while precipitation had only a marginal effect. For HR, significant effects were found for precipitation and clipping × warming.

The modeling analysis showed that none of the three-way interactions among temperature, carbon dioxide, and altered precipitation were substantial for carbon or water processes. However, many of the two-way interactions among the three factors were significant. In addition, wet sites generally had smaller relative changes in NPP, Rh, runoff, and transpiration but larger absolute changes in NEP than dry sites in response to the treatments. These modeling results suggest new hypotheses to be tested in multifactor global change experiments. Likewise, more experimental evidence is needed for the further improvement of ecosystem models in order to adequately simulate the complex interactive processes.

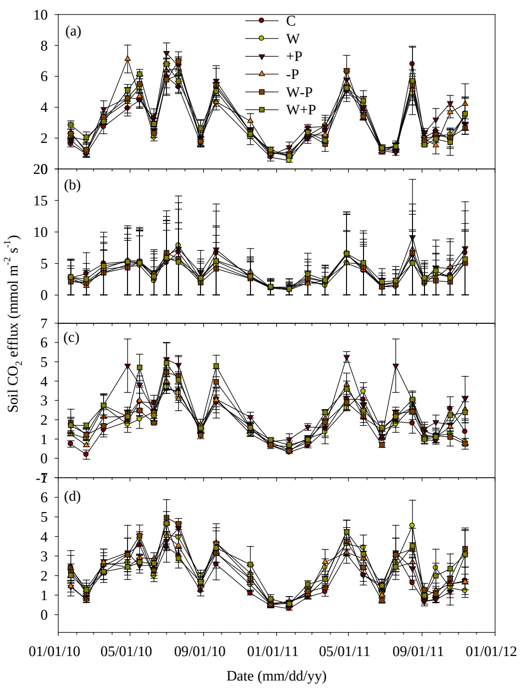

Fig 7. Seasonal and interannual variation of soil CO_2 effluxes from Jan 2010 to Nov 2011: (a) soil respiration for unclipped treatments; (b) soil respiration for clipped treatments; (c) soil heterotrophic respiration for unclipped treatments; and (d) soil heterotrophic respiration for clipped treatments.

Overall, preliminary data shows fewer interactions than expected between different climate change factors, which *may* allow future experiments and modeling efforts to be simplified to include only 2-way interactions, not 3-way interactions. However, doing so at this time would be premature, given the known differences between different ecosystem types and especially the high variability observed in soil respiration and whole ecosystem gas exchange. Additionally, initial results of global change experiments may differ during short- (1-3 years) and long-terms (~10+ years) time spans. Finally, our methods for decreasing or increasing precipitation rely on ambient rainfall and results can differ significantly between years.

4. Research products.

Research publications that were supported by this grant are listed in the next section. We have information on this experiment in our webpage: http://bomi.ou.edu/luo. Additionally, the webpage will serve as a portal for data sharing at the conclusion of the experiment.

5. Publications.

The NICCR grant permitted us to finish and/or partially support on-going publications as follows:

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6. Student degrees supported.
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Final Technical Report—November 14, 2011
Midwestern Regional Center of the Department of Energy's National Institute for Climatic Change Research

Agroecosystems: Effects of Changes in Climate, Carbon Dioxide, and Ozone Over the Central United States

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1. Abstract.

Terrestrial ecosystem models must be tested before being used to quantify effects of climate change on agroecosystems. Our goal was to capture the observed response of maize, soybean, and wheat to elevated carbon dioxide concentration, ([CO_2]) and ozone concentration ([o_3]) in the Agro-IBIS model using data from the SoyFACE facility and other published datasets. We then ran simulations across the Midwest and Great Plains. Elevated [CO_2] led to significant changes in the surface energy budget, with decreases in water loss to the atmosphere and increases in surface heat flux and belowground storage of water. New experimental work discovered that rising [o3] significantly increased both dark respiration of leaves and the slope (m) parameter of the Ball, Woodrow and Berry model of stomatal conductance. Stimulation of dark respiration at elevated [CO_2] combined with reduced photosynthesis to drive reductions in plant carbon balance and net primary productivity. Changes in stomatal function meant that water use efficiency decreased at elevated [o3] more than previously assumed. These key physiological responses are currently being used to drive predictions of how rising [o3] will alter biogeochemical cycles of the soybean agroecosystem under future elevated [o3] conditions.

2. Research Activities.

Our primary objective was to quantify changes in components of the energy, carbon, and water budgets within agroecosystems as they respond to projected changes in climate and increasing concentrations of carbon dioxide [CO_2] and tropospheric ozone [o_3] in the U.S. Midwest and Great Plains. We used the Agro-IBIS ecosystem model that incorporates the structure and functioning of major U.S. agroecosystems, to accomplish the following specific objectives:

1. Evaluate model estimates of corn and soybean agroecosystem responses to recent trends in climate with observations from the Bondville, IL and Rosemount, MN FLUXNET sites
2. Perform experiments to identify key physiological responses of soybean to elevated [o3] necessary to drive modeling of ecosystem processes by Agro-IBIS.
3. Evaluate model estimates of altered carbon and water cycling in soybean, corn and wheat with observations from FACE facilities that simulate future changes in [CO_2], [o_3] and rainfall

4. Evaluate how future changes in climate means and variability will affect regional energy, carbon, and water budgets of U.S. agroecosystems through Agro-IBIS simulations with datasets of projected regional climate change
5. Examine the cumulative response of agroecosystems to the concomitant changes in climate, climate variability, and elevated atmospheric [CO_2] and [o_3].

We evaluated output from the Agro-IBIS model with measurements of maize and soybean structure and functioning under ambient environmental conditions at the SoyFACE facility and Ameriflux sites in Bondville, IL and Rosemount, MN. While the model performed well over a number of growing seasons, we improved the simulation of soybean by implementing a new phenology algorithm that is based on work of Setiyono et al. (2007). We then calibrated the model based on leaf-level and canopy-level measurements of soybean, maize, and wheat at 550 ppm [CO_2] as well as a number of different ozone concentrations. To simulate the response of soybean to [o_3], we implemented an algorithm based on that of Sitch et al. (2007), as we had proposed to do; however, new results from manipulative experiments showed that ozone response in soybean is sensitive to other model parameters not included in the Sitch et al. algorithm. We pursued this development and have created an alternative algorithm that could be implemented into any ecosystem model that uses a mechanistic stomatal response to ozone concentration. We are continuing to evaluate results of this method with field and laboratory measurements.

Through collaborations with colleagues concurrently funded by NICCR, we have acquired a high resolution (~10 km) climate dataset for the period 1948-2007. Colleagues at University of Nebraska have recently corrected a bias in the radiation data and we are presently performing climate simulations with this new dataset. Agro-IBIS was run with datasets of future climate scenarios from (1) global climate models and (2) downscaled data from regional climate models. With both methods, historic yields were simulated to have larger temporal variability than in the observed record. Therefore, we are also modifying the historic climate dataset with anomalies based on trends in the future climate scenarios and will compare results to those using the two other datasets.

3. Research Highlights.

The ability of Dynamic Global Ecosystem Models to simulate ecosystem function is highly dependent on sound representations of leaf-level processes. Our research explored the relationship between g_s and *A*, h and [CO_2] in the context of rising atmospheric [o_3], and in conditions of simultaneous rises in [o_3] and [CO_2]. It was discovered that the sensitivity of g_s to *A*, h and [CO_2] increased with elevated [o_3], and that this effect was diminished as [CO_2] increased. As a result, the Ball *et al.* (1987) model and its derivatives will require reparameterization at elevated [o_3]. Without correcting for increasing sensitivity with [o_3] for the conditions described, predictions of the Ball *et al.* (1987) model will yield lower g_s than if parameterized for growth [o_3]. Due to the close relationship between g_s and transpiration (Bernacchi *et al.* 2007), higher estimates of g_s than expected may result in underestimation of transpiration and water use efficiency. In addition, we discovered that dark respiration of leaves was positively, linearly correlated with growth [o3]. This resulted in an exponential increase in the respiration to Vcmax ratio that is a key parameter in Agro-IBIS that was previously held as a constant. These key physiological responses are currently being used to drive predictions of how rising [o3] will alter biogeochemical cycles of the soybean agroecosystem under future elevated [o3] conditions.

Our initial simulation of Agro-IBIS at the SoyFACE facility, prior to modifications, showed an overestimation of soybean leaf area index (LAI) at [CO_2] of 550 ppm. This was expected as previous studies using these types of models show substantial increases in LAI at elevated [CO_2]. We found that modifying the value of Vmax improved the model results significantly. Despite accurate representation of LAI, hourly photosynthesis rates, internal [CO_2] within the leaf, and stomatal conductance, we were not able to correctly represent the change in soybean transpiration that occurs with elevated [CO_2]. This appears to be a limitation of the canopy equations that has been documented in other modeling studies. While our work to correct other variables has been primarily mechanistic, we used an empirical correction factor to bring our values of transpiration into agreement with measurements. Simulated transpiration decreases with [CO_2] of 550 ppm, which results in decreases in latent heat flux of 10-30 W m^{-2} and corresponding increases in sensible heat flux during the growing season. Simulated decreases in transpiration over maize were similar to those of soybean and were consistent with measurements with no modifications of parameters needed. Simulated decreases in transpiration over spring wheat were similar to those of soybean and were consistent with measurements (Kimball et al. 1999) with similar modifications of parameters as soybean.

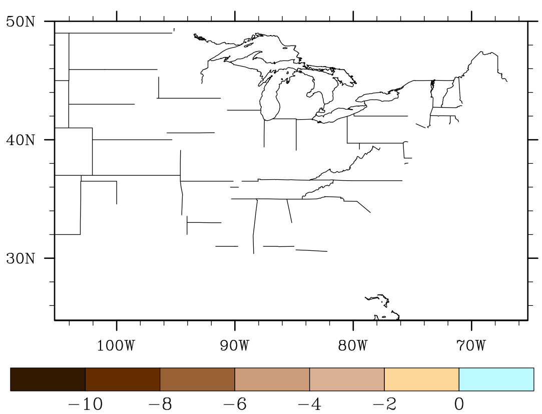

Figure 1: Mean (1953-2002) change in June-August corn and soybean monthly latent heat flux (W m-2) between a run with 550 ppm CO2 and 375 ppm simulated by Agro-IBIS and weighted by fraction crop cover. Hatching indicates differences that are statistically significant at p < 0.05.

Results of a 50-year simulation with the newly parameterized model over the U.S. Midwest show that the response of soybean and maize might have significant impacts on crop yield as well as water and energy budgets at regional scales. Simulations predict decreases in water loss from vegetation to atmosphere that are equivalent to ~ 10% of the mean August rainfall over the most intensively cropped regions of the domain (Figure 1). Annual average decreases over the region are equivalent to 8% of the discharge to the Mississippi River. These results suggest that similar vegetation models that do not vary model parameters under elevated [CO_2] conditions might underestimate future increases in soil water availability and discharge to streams.

With ozone concentrations near 40 ppb, model simulations show a minimal response of soybean, in agreement with SoyFACE observations. Agro-IBIS results show that ozone concentrations must rise to near 70 ppb before a response is seen. While productivity decreases, water is still conserved because of a decrease in stomatal conductance. Once our historic climate dataset is modified by anomalies predicted for the future, model simulations will combine effects of elevated [CO_2], [o_3], and climate change.

We evaluated ecosystem response to 20th climate in absence of changes to [CO_2] and [o_3] and continued evaluation of the Agro-IBIS model with satellite remote sensing data. In Twine and Kucharik (2008) we found that Agro-IBIS overestimates growing season LAI over broadleaf crops compared with MODIS estimates but underestimates values compared with AVHRR estimates. In Twine and Kucharik (2009), we examined the response of agroecosystems to climate variability over the two periods of 1950-2002 and 1982-2002 by minimizing the effects from management and trends in [CO_2], and by focusing on the effects of trends in temperature and precipitation on trends in net primary productivity. Our results provide further evidence supporting observational results that suggest 20 - 25% of recent crop yield trends can be explained by changing climate, and suggest that over the past several decades, climate changes have favored increased crop productivity in most agroecosystems of the central U.S. with the exception of winter wheat.

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4. Research Products.

A global version of the IBIS model continues to be made available at the University of Wisconsin Center for Sustainability and the Global Environment website to outside investigators who wish to check previous published results:
http://www.sage.wisc.edu/download/IBIS/ibis.html
Parameters that required modification in the Agro-IBIS model will be listed on Twine’s research website as well as through publications. This project funded the organization of a dataset of measurements made at the SoyFACE facility (collated from multiple investigators from previously published results) that may be made available to other crop modelers (particularly through the AgMIP model intercomparison project).

5. Publications.

Twine, T.E., and C.J. Kucharik, 2008. Evaluating a terrestrial ecosystem model with satellite information of greenness. *Journal of Geophysical Research-Biogeosciences*, 113, G03027, doi:10.1029/2007JG000599.

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Twine, T.E., J. Bryant, A. Leakey, K. Richter, and C. Bernacchi, 2011. Impacts of elevated CO2 concentration o productivity and surface energy budget in U.S. Midwest soybean and maize ecosystems, *to be submitted to JGR-Biogeosciences.*

Leakey A.D.B., Richter, K., A. Betzelberger, C.J. Bernacchi, T.E. Twine, E.A. Ainsworth (2012) Altered stomatal sensitivity to photosynthetic and environmental signals drives decreases in canopy and ecosystem water use efficiency of soybean with rising [o3] *to be submitted to PNAS*

Richter K. and A.D.B. Leakey (2012) Growth at elevated [CO_2] ameliorates the changes in sensitivity of stomatal conductance to photosynthetic and environmental signals at elevated [O_3] *to be submitted to Plant, Cell & Environment*

6. Student Degrees Supported.

Jarod Bryant, M.S. in Land and Atmospheric Sciences (UMN), January 2011. Thesis title, "*Biophysical Effects on U.S. Soybean Agroecosystems From Increasing Carbon Dioxide Concentration*".

Katherine Richter, M.S. in Plant Biology (UIUC), July 2011. Thesis title, "*Stomatal Sensitivity to Photosynthetic and Environmental Signals in Glycine Max Grown at Elevated Atmospheric Concentrations of CO_2 and O_3*".

Final Report to Midwestern Regional Center of NICCR

Short and long-term temperature acclimation of roots systems in woody plants and the moderation of warming-induced enhancement of soil CO_2 efflux

April 1, 2008 – November 30, 2013

Principal Investigator: Andrew J. Burton, Michigan Technological University, Houghton, MI, ajburton@mtu.edu, (906) 487-2566

Co-investigator: Erik Lilleskov, US Forest Service Northern Research Station, Houghton, MI, elilleskov@fs.fed.us. 906-482-6303 ext 22

1. Abstract (required).

Our overall objective was to assess the degree to which temperature acclimation occurs in root systems of a variety of woody plants and determine if such acclimation is a short-term, direct physiological adjustment to warmer temperatures (days to months) or a longer term response to changes in nutrient, moisture and C availability, and mycorrhizal status as the ecosystem adjusts to long-term warming (years). If root system respiration does not acclimate to warmer soil, the amount of C respired could increase greatly, leaving less C for other uses, including aboveground growth. To understand both immediate and long-term effects, study sites with 0 to 20 years of experimental soil warming (+5 ^{o}C) were utilized. Temperature acclimation did not occur for specific respiration rates of fine roots (< 1 mm) in response to seasonal changes in soil temperature, but did occur in the first few years of experimental warming in Michigan sugar maple forests. Experimental tests of potential mechanisms suggest that this was due, as least in part, to adenylate control. Through this mechanism, root respiration would be down-regulated to match the work required of the root system for nutrient uptake and assimilation. Dry conditions created by soil warming also significantly affected specific root respiration. In longer-term warming in mixed hardwood forests at Harvard Forest, fine-root specific respiration in warmed soil did not show evidence of thermal acclimation and was much higher than that for control treatments. However, overall carbon allocation to root respiration for soil warming treatments was still constrained, in this case by a large compensating decrease in fine root biomass. This resulting adjustment in ecosystem scale root respiration actually enabled an increase in aboveground productivity. At both study locations, mycorrhizal hyphal respiration and biomass production tended to decrease with soil warming, leading to reduced overall mycorrhizal respiration in warmed soil. Warming caused an initial increase in soil respiration and N mineralization in the Michigan study, which declined rapidly over time. Soil decomposer enzyme activity followed a similar trend. Overall soil fungal and microbial biomass were decreased by soil warming and increased by moisture additions. A review of vegetation models commonly used as components of earth systems models indicates that only a few allow plant tissue respiration to acclimate to warmer conditions. Many allow respiration to increase exponentially with temperature and do not directly reduce root respiration in drier soil. Based on our consistent findings of constraints on root/mycorrhizal system respiration, model overestimates of the C flux associated with root and mycorrhzial respiration are likely, which could lead to underestimates of future net primary productivity.

2. Research Activities and Hypotheses.

We assessed the degree to which temperature acclimation occurs in root systems of a variety of woody plants and determined if such acclimation was a short-term, direct physiological adjustment to warmer temperatures (days to months) or a longer term response to changes in nutrient, moisture and C availability, and mycorrhizal status as the ecosystem adjusts to long-term warming (years). To understand both immediate and long-term effects, study sites with 0 to 16 years of warming at the beginning of the project were utilized. These included northern hardwood forests at the Ford Forestry Center in Michigan (MI), with warming initiated in September 2010, after a year of pre-treatment measurements, and mixed hardwoods at Harvard Forest (HF) that have been warmed (+5 ^{o}C) since 1991, 2003 and 2006. Measurements made included root, mycorrhizal and soil respiration; root, microbial and mycorrhizal biomass; soil enzyme activity; microbial community composition; N mineralization; and aboveground NPP. The MI experiment provided opportunities for additional collaborative research that enabled us to include measurements of sapflow and wood decomposition.

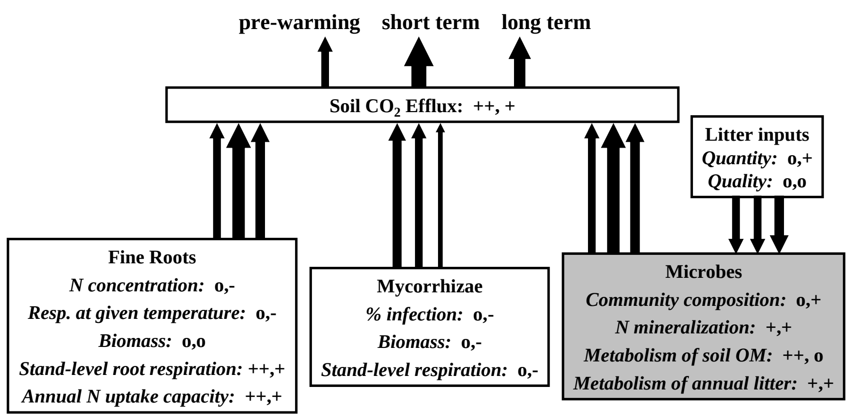

Fig. 1. Conceptual model of our primary hypotheses regarding the effects of soil warming on belowground ecosystem processes, when moisture is not limiting. Alternative hypotheses are described in the text. Arrows for CO_2 fluxes and soil litter C inputs indicate the relative magnitudes of fluxes prior to warming; short-term fluxes in the days to first year following warming; and long-term fluxes after the ecosystem has equilibrated with altered soil temperature and moisture for several years. Symbols listed for root, mycorrhizal, microbial, and litter characteristics indicate hypothesized increases (+), decreases (-) or lack of change (o) in the short term (first symbol) and the long term (second symbol).

Our conceptual model (Fig. 1) hypothesized that warming will initially cause a large increase in soil respiration as both root and microbial respiration increase (Fig. 1), in the absence of immediate physiological acclimation in root respiration (H1). Over longer time periods, root respiration will adjust to warmer conditions, with newly formed roots having a lower metabolic capacity (specific respiration rate at a given temperature) and lower N (H2). At the ecosystem level, root respiration will be unchanged due to the combined effects of lower metabolic capacity and warmer conditions (a smaller machine will run faster). The result of this adjustment will be roots with lower N concentration and lower specific respiration rate at a given temperature on warmed plots, which respire at similar rates as roots on the control plots at any given time due to warmer ambient conditions. The increase in microbial respiration with warming will also lessen over time, as labile soil organic matter is exhausted; however microbial respiration rates will not fully return to pre-warming levels, due to more rapid cycling of ecosystem N, greater aboveground productivity, and shifts in microbial community composition that allow for more complete metabolism of annual litter inputs. With enhanced N availability, mycorrhizal abundance will decline (H3). This will reduce the contribution of mycorrhizae to soil CO_2 efflux and make more C available for aboveground productivity. The combined result will be a large temporary increase in soil CO_2 efflux, followed by a smaller, *but sustained* increase in annual soil respiration (H4). The level of increase in soil respiration will be lower than would occur if the root system had not adjusted to altered temperature. These predictions assumed sufficient moisture. Under dry conditions (warming with no water addition), ecosystem root respiration, soil respiration and NPP are all expected to be reduced by drought effects.

3. Research highlights.

In MI, warming began in late summer 2010 after 1.5 years of pre-treatment measurements. The forest is 100 years old and dominated by sugar maple (88% of basal area). Three replicate 10 m x 10 m plots exist for each of the four combinations of soil warming (ambient, +4 to 5 ^{o}C) and moisture (ambient, +30%). The use of overhead infrared heaters enabled examination of immediate soil warming responses, while avoiding disturbance effects from installation of heating cables. Measurements indicate we have consistently achieved our target soil temperature increase and maintained soil moisture on the heat+water treatment at levels approximately those in the control treatment.

H1. Root respiration will not acclimate to short-term changes in soil temperature.
Corollary 1a: *Root respiration will not acclimate to seasonal changes in soil temperature.*
Corollary 1b: *Root respiration will not acclimate within several days to weeks following initiation of soil warming treatments.*

In MI, there were no pre-existing differences in specific fine-root respiration rates among the groups of plots assigned to each treatment. After the heating lamps and sprinklers had been installed, but before treatments were initiated, respiration was measured on four additional sample dates. Again, no differences were found among the groups of plots assigned to each treatment, indicating fine-root respiration rates had not been altered by disturbance from installing infrastructure (Jarvi and Burton 2013).

Using data from all treatments prior to initiation of soil warming and from the control plots after treatments were initiated, specific fine-root respiration was shown to exhibit an exponential increase to seasonal changes in soil temperature with a Q_{10} of 2.7. Specific fine-root respiration at the 18^{o}C reference temperature, used as an indicator of metabolic capacity, was not correlated with ambient soil temperature for the unheated control plots during the study, indicating that acclimation did not occur in response to seasonal changes in soil temperature (Fig. 2 and Jarvi and Burton 2013).

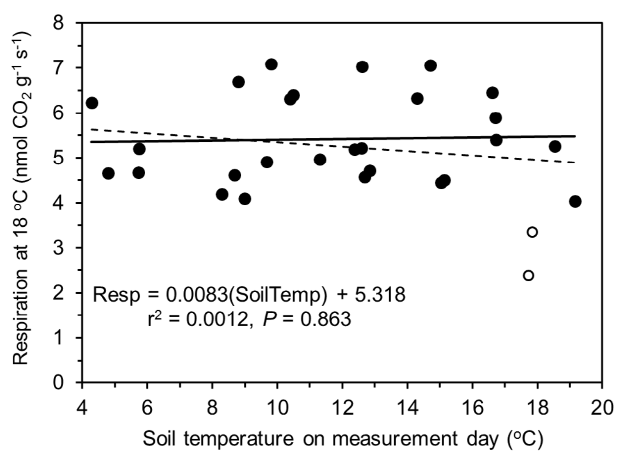

Fig. 2. Relationship between specific fine-root respiration at the 18 ^{o}C reference temperature and ambient soil temperature for the control plots. The closed circles and solid regression line indicate periods of adequate soil moisture. The open circles indicate very dry sample dates in August and September 2011. The dashed regression line is for all data. The regression relationship displayed indicates no acclimation in root respiration in association with seasonal variations in soil temperature when soils are moist (P = 0.863). Even when the very dry sample dates are included, there is not a significant relationship between fine-root metabolic capacity (and soil temperature (P = 0.348).

In contrast to our hypotheses, specific root respiration in MI did show evidence of acclimation during the first measurements made, within weeks after warming was initiated. It is unclear regarding the degree to which this response was related to drier soils versus physiological acclimation, but as warmng proceeded, it became clear that physiological acclimation was occurring (see H2, below).

H2. Root respiration rates will adjust to long-term elevated soil temperatures, with newly formed roots having a lower metabolic capacity (respiration rate at a given temperature) and lower N.

Corollary 2a: *In elevated temperature treatments, annual N availability may greatly exceed that in unheated plots, but it will ultimately return to levels only slightly above those in the control plots.*

Corollary 2b: *Specific rates of root respiration and root N uptake will adjust (become lower at a given temperature), such that on an annual basis stand-level root respiration and N uptake potential are slightly greater in heated than in unheated plots. Root biomass will be unchanged by warming.*

Contrary to our hypothesis, we have found fine-root specific respiration rates and root N to be significantly higher in warmed soil at HF (Fig. 3, also Burton et al. 2008). However, a compensating reduction in fine root biomass, also contrary to our hypothesis, resulted in lower total ecosystem root respiration (Fig 3, also Zhou et al. 2011). This constraint on respiratory CO_2 loss, along with greater N availability from increased soil organic matter decomposition, enabled an increase in aboveground growth at HF (Melillo et al. 2011).

At the MI site, we have found enhanced N mineralization (up to 80%), greater soil respiration (up to 50%) and increased root respiration (Fig. 3), but no reduction in surface fine root biomass through 3 years of warming. As a result, roots are returning more C to the atmosphere (Fig. 3, lower plate), leaving less for NPP (aboveground growth is reduced 40% in heated treatments). The enhancement of soil respiration and N mineralization are declining over time, as hypothesized. A reduction in surface fine root biomass may eventually occur at MI, if the experiment is continued. Reduced surface fine root biomass was clearly apparent by year 5 at the HF large plots.

Through 3 years, we have consistently seen greater specific root respiration rates in the MI forest (Fig 3, upper plate), but not to the degree that would be expected for a 5 ^{o}C temperature increase (Jarvi 2011, Jarvi and Burton 2013). Some of this apparent acclimation is due to drier soils, but when the effects of soil moisture are accounted for, our results still suggest partial acclimation has occurred (Fig. 4), as

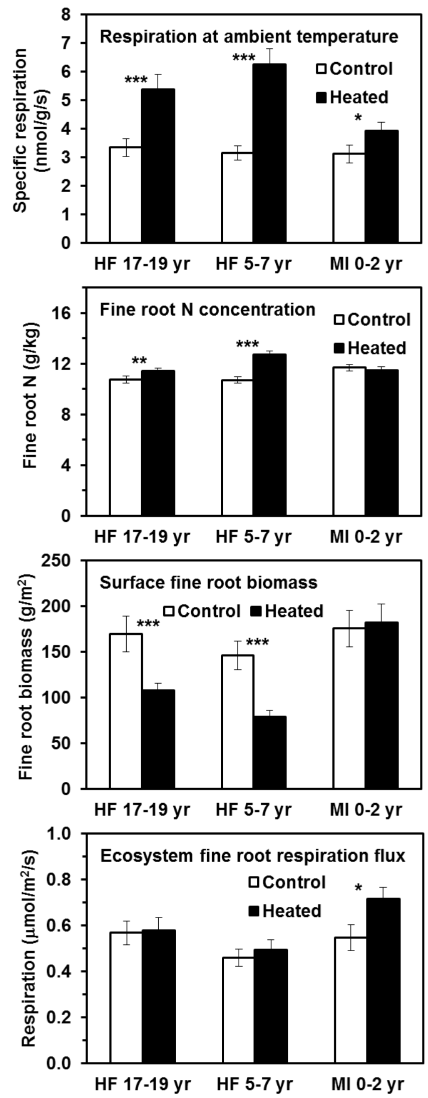

Fig. 3. Fine root specific respiration rates at ambient soil temperature; root N concentrations; root biomass; and ecosystem fine root respiration (specific respiration x biomass) for control and heated (+5 ^{o}C soil temperature) plots at Harvard Forest (HF) and Michigan (MI) soil warming experiments. Values are means for 14 (HF) and 11 (MI) sample dates. Error bars are standard error. Years of warming prior to measurements are indicated in the y-axis titles. Significance at *P* of 0.001, 0.01 and 0.05 is indicated by ***, **, *, respectively.

indicated by lower respiration rates for the heat and heat+water treatments at the 18 °C reference temperature. This slight acclimation could be due to substrate limitation (Atkin et al. 2000), with C availability to roots being insufficient to allow all portions of the root system to respire at their enzymatic potential. Adenaylate control is another possible mechanism, where the production of ATP is in excess of demand for root metabolic processes for nutrient uptake and transport.

We tested these potential acclimation mechansims in 2013 using additions of exogenous sugars to root samples to test for substrate limitation and treatment with a decoupling agent (CCCP, Drake et al. 2008) to test for adenylate control. CCCP dissipates the H^+ gradient of the mitochondria and allows respiration to proceed without production of ATP, eliminating reductions in respiration associated with low levels of ADP that can occur when ATP production exceeds cell metabolic energy requirements. Glucose additions had no effect on fine-root respiration ($P = 0.94$) indicating that substrate limitation was not constraining fine-root respiration. CCCP increased fine-root respiration for all treatments ($P < 0.001$), indicating some degree of adenylate control was present in all cases. However, there also was an indication that CCCP caused greater enhancement of respiration for roots from heated soil ($P = 0.10$). The greater relative increase in respiration after CCCP additions to roots from heated soil suggests that fine-root respiration is being constrained by the amount of work being performed by the root system, enabling the above- and belowground allocation of C to remain in balance.

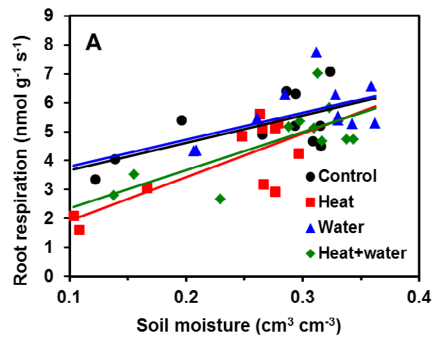

Fig. 4. Relationships in the MI warming x moisture addition experiment of fine root specific respiration at a reference temperature of 18 °C to soil moisture. Respiration at the reference temperature is used as an index of metabolic capacity. Soil moisture affected root respiration for all treatments, but slight acclimation (lower regression lines) is apparent for the two treatments with warmer soil.

H3. In the absence of water stress, mycorrhizal fungal biomass will decline with warming as a response to decreased C availability and increased nutrient supply. Longer-term community change will lead to dominants with lower tissue-specific respiration rates at higher temperatures.

Corollary 3a: *Mycorrhizal fungal specific respiration rates will increase in response to warming, but the ecosystem C flux from mycorrhizal respiration will decline due to lower biomass.*

Corollary 3b: *Mycorrhizal fungal community change will be evident for long-term warming.*

Corollary 3c: *Species dominant under higher temperatures will have lower tissue-specific respiration rates than species dominant under lower temperatures. (This last corollary will only be tested if Corollary 3b is found to be true)*

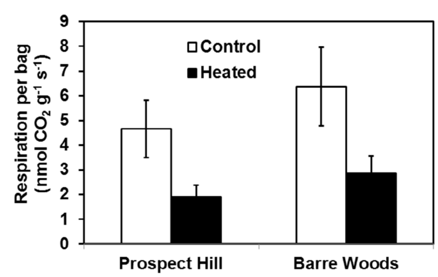

Fig 5. Mycorrhizal hyphal respiration per ingrowth bag from Harvard Forest in 2011. Error bars represent one standard error. Values for heated plots are significantly lower ($P < 0.05$) than control values for both the Prospect Hill (warmed since 1991) and Barre Woods (warmed since 2003) locations.

Hyphal respiration and biomass tended to decrease with soil warming at HF (Kratz 2014), leading to reduced overall mycorrhizal respiration in warmed soil (Fig. 5). This suggests that fungal hyphae adjust to higher temperatures by decreasing the amount of carbon respired and the amount of carbon stored in biomass. It also contributed to constraint of belowground C allocation under warming, enabling enhanced productivity aboveground. At the MI site, results from the hyphal in-growth bag studies indicated that AMF hyphal growth and respiration responded negatively to elevated temperature and positively to increased moisture inputs (Kratz 2014). Tissue specific respiration rates at ambient soil temperature for fungal hyphae from warmed soil at both HF and MI were equal to or lower than those from unwarmed soil. We have not been able to determine if this was due to a shift in community composition to species with lower inherent respiration at a given temperature. Other possibilities include thermal acclimation of the existing fungal community or a reduction in C availability for mycorrhzial fungi, due to constraints imposed by the host plant.

H4. Large initial increases in soil respiration with warming will decline to more moderate increases in soil respiration, which will be sustained in the long term.

Corollary 4a: *Elevated soil temperatures and increased soil moisture both will cause large short-term increases in annual soil CO_2 efflux on plots receiving heating and/or moisture additions.*

Corollary 4b: *Cycling of litter inputs to heated plots will increase in the long term.*

Corollary 4c: *After several years, annual soil CO_2 efflux on warmed plots will equilibrate moderately above control levels.*

As predicted, large initial increase in soil respiration occurred immediately after the initiation of warming in September 2010 in MI and then declined over time. By 2012 and 2013, rates for heated treatments were only slightly, and not significantly, elevated relative to the control treatment (Fig. 6). Moisture addition influenced soil respiration on specific dates, but not on an annual basis. The slight degree of enhancement for soil respiration in 2012 and 2013 with warming is consistent with contributions of the moderately greater root respiration still occurring during those years, due to only partial acclimation of root respiration.

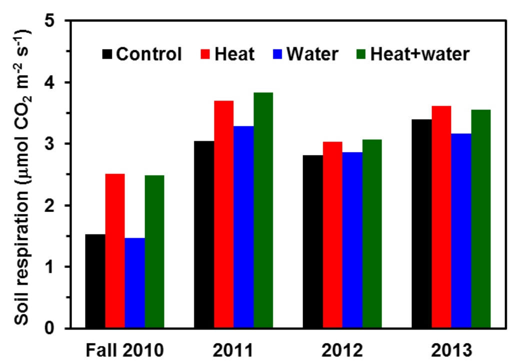

Fig 6. Mean annual soil respiration rates for the MI warming x moisture addition experiment. Values for heated plots are significantly lower ($P < 0.05$) than control values during fall 2010 and 2011.

Net N mineralization was significantly elevated throughout the experiment, but the degree of enhancement declined over time. In concert with enhanced organic matter decomposition, soil enzyme activities tended to be higher in heated versus unheated treatments in 2011 and 2012 at MI (Kratz 2014). Enzymes examined included cellobiosidase, β-glucosidase, acid phosphatase, NAGase, phenol oxidase, and peroxidase. There were significant temporal variations in enzyme activity and microbial biomass estimates. In agreement with a lessening effect of warming on soil respiration and N mineralization over time, enhancement of soil enzyme activity also was less in 2012 than in 2011. When microbial biomass was estimated using chloroform fumigation extractions there were no differences between experimental treatments and the control. When PLFA analyses were used to estimate microbial biomass, we found that biomass responds negatively to higher temperatures and positively to moisture addition. This pattern was present for both bacteria and fungi.

Additional Research Activities

The MI experiment provided opportunities for additional collaborative research that enabled us to include measurements of sap flow (Dr. Molly Cavaleri) and wood decomposition (Dr. Martin Jurgensen). Sap flow data from 2011 confirmed our initial expectations, showing a decline in tree transpiration as a result of warming-induced dry soils, but no direct effect of warming when moisture is added back to the system in the heat+water treatment (Fig 7). During 2012, however, both the heat and heat+water treatments had decreased levels of water use when compared to the control, likely the result of moderate regional drought further reducing available soil water. During 2013, the heat-only treatment had decreased water use, while the heat+water treatment had higher rates of water use compared to the control, likely the result of very moist growing season conditions. Overall, this study shows that increased temperature alone has minimal effects on the water uptake rates of sugar maple when water is plentiful, but that warming-induced drought effects could potentially exacerbate sugar maple sensitivity to climate change and potentially increases the prevalence of crown dieback. Decreasing soil moisture can induce water stress, leading to stomatal closure and decreased transpiration (Holscher et al. 2005), and stomatal behavior was found to be especially sensitive to declines in soil moisture in sugar maple (Hinckley et al. 1979).

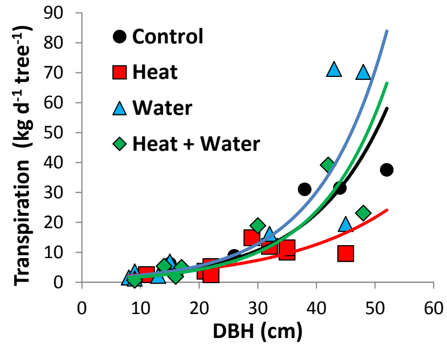

Fig. 7. Mean whole-tree water use per day by tree diameter (DBH) class at the MI sugar maple site in July and August. Warming-induced drought (Heat) decreased transpiration rates, especially in large trees. Trendlines are exponential, all with $r^2 > 0.6$.

Decomposition of wood stakes varied greatly both spatially and temporally. With respect to the treatments, warmer soil, and especially warmer and wetter conditions, were expected to increase wood decomposition. Instead, warming did not significantly increase decomposition and warming with moisture addition caused a slight decline. We suggest that enhanced N availability under warming led to suppression of basidomycete white rot fungi involved in wood decay, and currently are investigating this possibility. A similar occurrence occurred in a long-term N addition study located in a sugar maple forest near the MI warming site (Lyons 2012).

We also examined specific respiration rates for fine roots (<1 mm) of tamarack, black spruce, and leatherleaf in drained, wet and control areas of a poor fen peatland in Upper Michigan. Specific root respiration (nmol CO_2 g^{-1} s^{-1}) was 31% greater for the wet plots than controls and little changed in the drained plots. Woody fine root biomass was 215, 182, and 131 g m^{-2} for the drained, wet, and control , respectively, of which, 16%, 5%, and 10% consisted of tree roots (Carruthers et al. 2014). Ecosystem root respiration was elevated in both wet and drained treatments, with 0.31 and 0.33 μmol CO_2 m^{-2} s^{-1}, respectively, compared to the 0.17 μmol CO_2 m^{-2} s^{-1} in the control (Carruthers et al. 2014). All species contributed to these increases in ecosystem root respiration. This peatland clearly responded to changes in water table, but contrary to our hypothesis both the drained and wet areas has greater total ecosystem carbon flux. If woody tree encroachment continues in drained areas, contributions from tree root biomass may continue to increase in importance. We suggest care in using smaller chambers to examine net ecosystem exchange (NEE) in peatlands for which trees are encroaching, as chambers that do not fit over whole trees will capture root respiration but not other components of the tree's net carbon exchange. This could lead to overestimates of the contributions of peat decomposition to within chamber NEE.

4. Research products.

Our project web site can be found at http://forest.mtu.edu/burtonlab/Warming.html. As data sets are published they will be made available on the project page. In addition, data from research at Harvard Forest is available in the data archives on their website (project HF171 under "Long-Term Measurements" at http://harvardforest.fas.harvard.edu/data-archive).

5. Publications.

Burton, A.J., J.M. Melillo and S.D. Frey. 2008. Adjustment of forest ecosystem root respiration as temperature warms. J. Integr. Plant Biol. 50:1467-1483.

Burton, A.J., J.C. Jarvey, M.P, Jarvi, D.R. Zak, and K.S. Pregitzer. 2012. Chronic N deposition alters root respiration-tissue N relationship in northern hardwood forests. Global Change Biology 18:258-266.

Carruthers, K.M., M.P. Jarvi, R.A. Chimner, and A.J. Burton. 2014. Ecosystem respiration responses to changes in water level in a northern poor fen peatland may be partially attributed to woody fine root respiration. Ecosystems *in review.*

Jarvi, M.P., and A.J. Burton. 2013. Acclimation and soil moisture constrain sugar maple root respiration in experimentally warmed soil. Tree Physiology 33:949-959.

Jarvi, M.P., and A.J. Burton. 2014. Sugar maple fine-root respiration is mechanistically constrained by adenylate control after 3 years of experimental soil warming. Plant, Cell and Environment *in review*.

Melillo, J.M., S. Butler, J. Johnson, J. Mohan, P. Steudler, H. Lux, E. Burrows, F. Bowles, R. Smith, L. Scott, C. Vario, T. Hill, A. Burton, Y. Zhou, and J. Tang. 2011. Soil warming, carbon-nitrogen interactions and forest carbon budgets. Proceedings of the National Academy of Sciences 108:9508-9512.

6. Student degrees supported.

Doctoral Students

Alex Collins. Doctoral student since January 2011. Research Topic: Inter-annual Differences in the Water Use of Mature Sugar Maple in Response to Experimental Warming and Irrigation.

Mickey Jarvi. Doctoral student since January 2012. Research Topic: Effects of Climate Change on Root System Ecophysiology and Ecosystem Productivity in Northern Hardwood Forests.

Carley Kratz. PhD May 2014. Impacts of Climate Change on Soil Microorganisms in Northern Hardwood Forests. Doctoral Dissertation, Michigan Technological University, Houghton, MI.

Masters Students

Mickey Jarvi. MS December 2011. The Effects of a Changing Climate on Root Respiration of Woody Plants in Sugar Maple Forests and Northern Peatlands. MS Thesis, Michigan Technological University, Houghton, MI.

Alida Mau. MS student since August 2013. Research Topic: Photosynthetic Responses of Sugar Maple Trees to Increased Temperatures.

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Hinckley, T.M., P.M. Dougherty, J.P. Lassoie, J.E. Roberts, and R.O. Teskey. 1979. A severe drought: Impact on tree growth, phenology, net photosynthetic rate and water relations. Am. Midl. Nat. 102: 307-316.

Holscher, D., O. Koch, S. Korn, and Ch. Leuschner. 2005. Sap flux of five co-occurring tree species in a temperate broad-leaved forest during seasonal soil drought. Trees 19:628-637.

Jarvi, M.P. 2011. The Effects of a Changing Climate on Root Respiration of Woody Plants in Sugar Maple Forests and Northern Peatlands. MS Thesis, Michigan Technological University, Houghton, MI.

Jarvi, M.P., and A.J. Burton. 2013. Acclimation and soil moisture constrain sugar maple root respiration in experimentally warmed soil. Tree Physiology 33:949-959.

Jarvi, M.P., and A.J. Burton. 2014. Sugar maple fine-root respiration is mechanistically constrained by adenylate control after 3 years of experimental soil warming. Plant, Cell and Environment *in review*.

Kratz, C.J. 2014. Impacts of Climate Change on Soil Microorganisms in Northern Hardwood Forests. Doctoral Dissertation, Michigan Technological University, Houghton, MI.

Lyons, B.J. 2012. Nitrogen Deposition Effects on Production and Decomposition of Coarse Woody Debris. MS Thesis, Michigan Technological University, Houghton, MI.

Melillo, J.M., S. Butler, J. Johnson, J. Mohan, P. Steudler, H. Lux, E. Burrows, F. Bowles, R. Smith, L. Scott, C. Vario, T. Hill, A. Burton, Y. Zhou, and J. Tang. 2011. Soil warming, carbon-nitrogen interactions and forest carbon budgets. Proceedings of the National Academy of Sciences 108:9508-9512.

Zhou Y., J. Tang, J.M. Melillo, S.M. Butler, and J.E. Mohan. 2011. Fine root standing crop and chemistry after six years of soil warming in a temperate forest. Tree Physiol. 31:707-717.

Final Report to the DOE National Institute for Climatic Change Research

Project Title: The interactive effects of elevated temperature and CO_2 applied under field conditions on a soybean ecosystem

PI: Carl J Bernacchi, University of Illinois
Co investigators: Bruce A. Kimball, USDA-ARS
Donald R. Ort, University of Illinois & USDA-ARS
Evan H. DeLucia, University of Illinois

1. Abstract

The funding provided was used to collect data as part of the Temperature by Free Air CO_2 Enrichment (T-FACE) at the Soybean FACE (SoyFACE) research facility in Champaign, IL over two growing seasons. This experiment investigated the interacting effects of increased canopy temperature (3.5 °C above background) and CO_2 concentration (180 ppm above mean global concentrations) on growth, physiology, and biogeochemical cycling for the soybean-maize agro-ecosystem. The increase in temperature was applied over two entire years using infrared heaters and the CO_2 fumigation during the growing season using FACE technology, with the first year being over *Glycine max* (soybean) and the second year over *Zea mays* (maize). For soybean, results show that elevated temperature decreases and elevated CO_2 increases photosynthesis, growth, and yields for soybean. When applied in combination, the elevated CO2 + elevated temperature treatment shows no differences in biomass or yields relative to the control. These results suggest that when applied in combination, the benefits of higher CO2 offset the negative impact of higher temperatures. None of the treatments had an impact on the overall above-ground growth of maize, however, the elevated temperature treatments reduced allocation to reproductive development thereby reducing yields. The elevated CO2 plot also showed a decrease in yields for maize, likely driven by warmer plant canopies during key reproductive stages resulting from reduced evapotranspiration.

2. Research activities

<u>Objective 1: To understand the impact that increases in [CO_2] and temperature will have on plant growth and development including underlying physiological mechanisms.</u>

Hypothesis 1a: Photosynthetic rates for soybean grown in the elevated temperature treatments will be lower than for the control temperature plots despite an increase in the temperature optimum of photosynthesis with higher temperature. Elevated [CO_2] combined with heating will result in higher rates of photosynthesis than any other treatment as a result of the suppression of photorespiration with elevated [CO_2] and the stimulation of reaction rates by higher temperature.

Activities 1a: We measured the temperature response of photosynthesis at three points throughout the growing season to determine the impact of the treatment combinations on carbon uptake. Accompanying these measurements were photosynthetic CO_2 response curves to identify changes in the underlying biochemistry of photosynthesis resulting from the treatments.

Hypothesis1b: Photosynthesis, growth and yield for maize will not be affected by an increase in CO_2 concentrations but elevated temperature will increase the carbon uptake and productivity as indicated from theoretical responses of C4 photosynthesis to temperature.

Activities: We measured gas exchange over the diurnal time course on six days during the growing season when the experiment focused on maize. The measurements were used to compare the physiological responses of carbon fixation at elevated CO_2 and temperature. Biomass and yield harvest were measured at the end of the growing season. Throughout the growing season, measurements of photosynthetic-CO2 response curves were collected to understand the key limiting processes to carbon assimilation in the CO2 and temperature treatments.

Hypothesis 2: The high temperature treatment will increase the incidence of moderate leaf temperatures and, if meteorological conditions are conducive, may result in extreme temperature induced, non-reversible damage to photosynthesis. Increased temperature coupled with decreased evaporative cooling in elevated [CO_2] will increase the frequency with which damaging and lethal leaf temperature limits are reached relative to the elevated temperature, control [CO_2] treatment.

Activities 2: We monitored environmental conditions to determine whether these situations arose. Even with the additional 3.5 °C heating, extreme/lethal temperatures did not occur.

Hypothesis 3: Leaf mitochondrial respiration (R_d) will be increased with elevated temperature and will be greatest when the elevated temperature treatment is combined with elevated [CO_2]. This increase, however, will be lower than predicted from the control temperature plots (following a Q_{10} relationship) as a result of acclimation of R_d to higher temperature.

Activities 3: We measured the temperature response of mitochondrial respiration using a differential oxygen analyzer in the first year (soybean) and using a modified gas exchange system (LI-6400, LI-COR, Inc., Lincoln, NE) during the second year (maize). These measurements were made 3 times throughout each growing season.

Hypothesis 4: An increase in temperature will result in a lower stomatal conductance (g_s) relative to control (i.e., ambient [CO_2] and ambient temperature). The combination of heating and CO_2 enrichment will lead to lower g_s than for the heated only plots. Despite the lower g_s with heating (with or without [CO_2]), soil moisture will be lower in the heated plots as a result of more evaporative demand.

Activities 4: We measured gas exchange over the diurnal time course on six days throughout each growing season. These measurements identify the impact of the treatment combinations on photosynthetic uptake of CO2 and stomatal conductance. We also measured soil moisture to 1m depth using a Frequency Domain Reflectometry probe (Diviner 2000, Sentek). These measurements were made three times per week during the growing season.

Hypothesis 5: Elevated temperature will suppress NPP, but the increase in photosynthesis with the interacting effects of [CO_2] and temperature will dominate and lead to the highest NPP of all treatments.

Activities 5: We measured leaf area index and use these non-destructive measurements to determine growth using allometric analyses determined from larger plots. This is the only means to assess growth over the growing season without compromising the experiment. We also measured end of season biomass and yields. Minirhizotron tubes were installed to measure in biweekly intervals the impact of increased CO_2 and temperature on root growth.

Objective 2: To understand the impact that increases in [CO_2] and temperature will have on annual carbon cycling.

Hypothesis 1: Ecosystem heating will permanently increase the activity of soil heterotrophs, resulting in an increase in heterotrophic respiration (R_{het}) that will be sustained until labile soil C is substantially depleted.

Activities 1: We partitioned soil respiration into autotrophic (R_{aut}) and heterotrophic (R_{het}) components by measuring CO_2 flux from soil (R_{tot}) and from soil from which roots have been excluded (R_{het}). R_{aut} is computed as the difference between these fluxes. These measurements were taken biweekly since heating began in June 2009. To observe the depletion of labile soil C, we collected soil samples once per season to be incubated in the laboratory, where microbe-available C can be calculated as the cumulative CO_2 flux over time when the sample is incubated without new substrate additions.

Hypothesis 2: Heating-induced activity and the subsequent decline in SOM availability will change the structure and function of the soil microbial community.

Activities 2: We collected soil samples three times per season to assess microbial biomass, microbial community metabolic diversity, and metagenomic microbial community structure. We performed multivariate analyses to assess how the size and genetic makeup of soil microbial communities change with temperature and SOM availability

Hypothesis 3: Multi-factor field experiments can improve the parameterization of process-based environmental models.

Activities 3: We are using the DAYCENT carbon storage model to predict the effects of climate change of soil carbon cycling over timescales longer than the T-FACE experiment will run. After two years it is apparent that DAYCENT's predictions are deviating from the observed conditions. We are using the datasets from testing hypotheses 1 and 2, along with observations from other investigators at T-FACE, to examine how DAYCENT's predictions could be improved. For example, DAYCENT currently uses a very simple black-box model of microbial activity. We will use results from Objective 2, Hypothesis 2 to determine whether a model that considers microbial diversity as well as biomass could give improved predictions.

Major deviations from original timeframe:

There were no deviations from the original timeframe. We did change the experiment in the second year to increase the CO2 and temperature over maize and not soybean. Since this experiment operates according to typical agronomic practices, the crops are rotated every year. The costs to upgrade the power in the section of the field where soybean was planted in 2010 prohibited us from continuing this experiment over soybean. Thus, T-FACE remained in its original location and was situated over maize in the second year.

3. Research highlights

This experiment helped to shed light on the responses of both maize and soybean, two agronomically important species that, together, dominate the Midwestern landscape.

Key results are as follows:

a. Objective 1

Combined increases in CO2 and temperature in soybean have a synergistic impact on net photosynthesis but this does not translate to increased yields.

We measured leaf level gas exchange during the 2009 growing season when soybean was exposed to elevated CO2, increased temperature, and a combination of elevated CO2 and increased temperature. Overall, the CO2 + temperature treatment resulted in slightly higher net carbon uptake relative to the elevated CO2 treatment alone, but the increase was less than predicted. More importantly, this increase in photosynthesis did not translate into higher biomass or yields. In fact, the CO2 + temperature treatment, while higher than the control, drove biomass and yields lower than elevated CO2 alone (Figure 1).

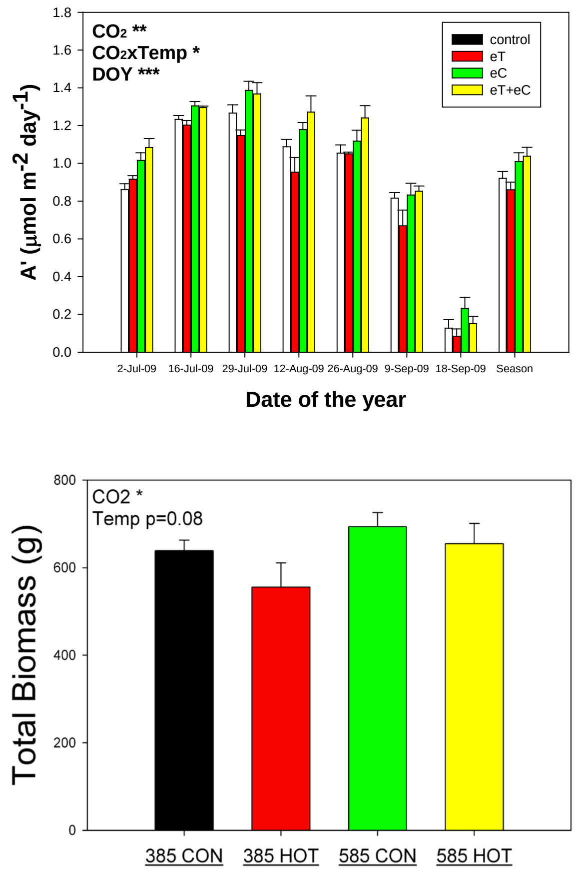

Figure 1. (top) Net daily leaf level carbon uptake measured on six days during the 2009 growing season and averaged over the growing season for soybean grown under control, elevated temperature, elevated CO2 and elevated CO2+temperature. (bottom) Biomass data collected at the end of the 2009 growing season for both stem + pod biomass

Maize photosynthesis does not respond to increases in CO2 and decreases with temperature.

Despite our initial predictions, growth in elevated temperature results in lower

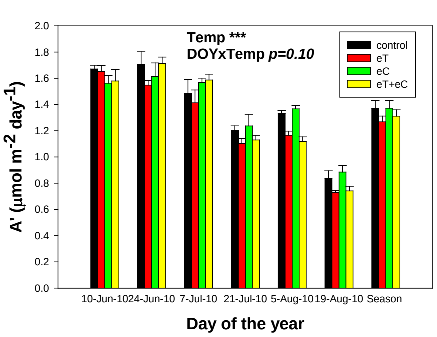

Figure 2. Daily integrated rates of photosynthesis for maize grown under control, elevated temperature, elevated CO2 and elevated CO2+temperature

photosynthetic rates in maize (Figure 2). This is likely driven by down-regulation of key photosynthetic enzymes, however, analysis of leaf photosynthetic respons[redacted]urves in maize are still being performed.

Maize above-ground biomass is unaffected by elevated CO2, elevated tem[redacted]rature, or CO2+temperature, however partitioning of the above-ground biomass in[redacted]ield is lower for all treatments.

Biomass measurements collected during the 2010 growing season shows that there are no differences in above-ground biomass for maize grown in any of the imposed treatments (Figure 3). However, the partitioning of the above-ground biomass differed for each of the treatments with all treatments resulting in lower yields, but more so for the elevated temperature plots. The lower yields in the high temperature plots are attributed to the temperature sensitivity of reproductive organs.

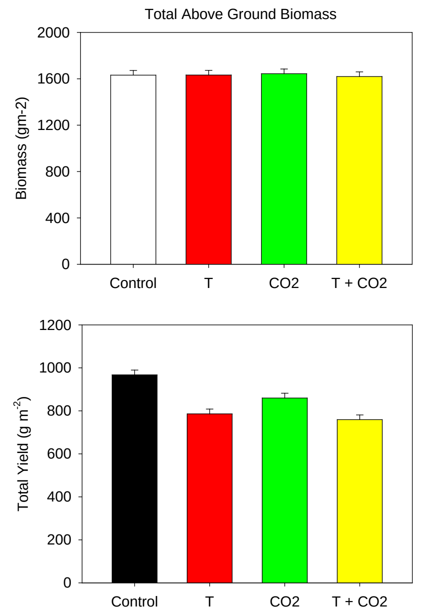

Figure 3. (top) Total above-ground biomass and (bottom) total harvested yield measured at the end of the 2010 growing season. Bar colors are as in Figure 2.

Objective 2.
Initially, higher temperatures increase the rate of soil respiration, but this effect is minimized over time.
Model predictions of soil heterotrophic respiration using the DAYCENT model refects accurately only one year of measurements.

Frequent measurements of soil respiration showed that, overall, there were no long-term net effects of increased temperature on soil respiration (Figure 4). Further, the disparity between the modeled and measured values shows the need for improved model parameters, which futher analysis of the data collected as part of this experiment will provide.

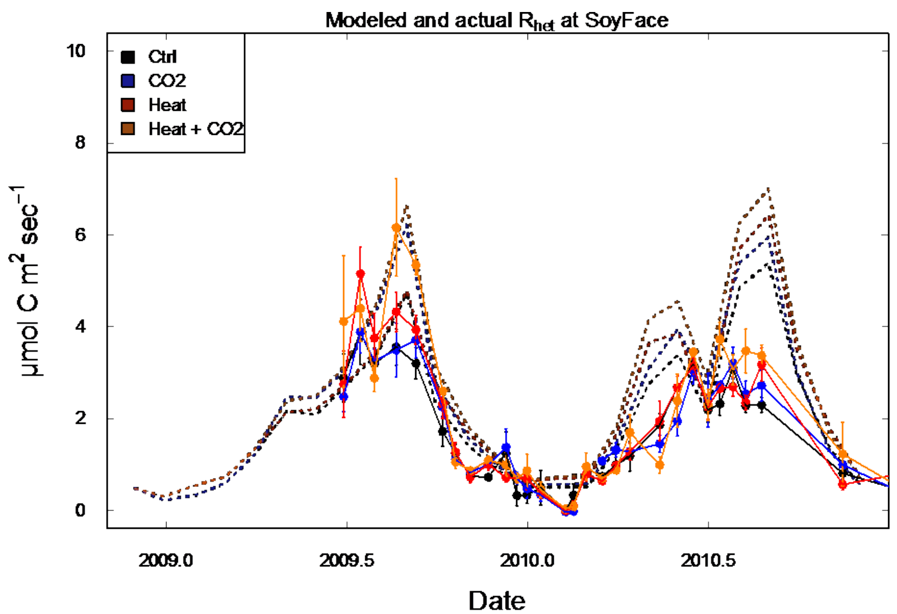

Figure 4. Heterotropic respiration (Rhet) measured over two years of treatment (closed symbols) for the control, elevated temperature, elevated CO2 and elevated temperature + CO2 treatments at SoyFACE. Also shown is Rhet predicted using the DAYCENT model (dashed lines).

4. Research products

Ruiz Vera UM, D Rosenthal, M Siebers, CJ Bernacchi, and DR Ort. Smaller than expected increases in integrated photosynthesis and biomass for plants grown at elevated CO2 and temperature under fully open air CO2 fumigation. Selected Presentation, Ecological Society of America Annual Meeting, Pittsburg, PA, August 2010.

Bernacchi, CJ. Managed ecosystem responses to climate extremes: current approaches and future directions. Invited Symposium, Ecological Society of America Annual Meeting, Pittsburg, PA, August 2010.

Bernacchi, CJ. Understanding photosynthetic responses to climate change in the context of rising CO_2. Invited Talk, International Congress on Photosynthesis, Bejing, China, August 2010.

Black CK, ,SC Davis, CJ Bernacchi, EH DeLucia. Heterotrophic respiration from soil increases with atmospheric carbon dioxide and temperature. Presented at the First Integrated Network for Terrestrial Ecosystem Research on Feedbacks to the Atmosphere and ClimatE (INTERFACE) Workshop, Captiva Island, FL, Feb 2011.

Bernacchi, CJ. Understanding photosynthetic responses to climate change in the context of rising CO_2. Invited Talk, Chinese Academy of Science, Shanghai, China, March 2011.

Ruiz Vera UM, M Siebers, D Rosenthal, S Gray, DR Ort and CJ Bernacchi. Effects of elevated temperature and CO2 on gas exchange and chlorophyll fluorescence in soybean (Glycine max (L.) Merr.) and maize (Zea mays) grown under open-air field conditions. Invited talk, American Society of Plant Biology Annual Meeting, Minneapolis, MN, August 2011.

Black CK, ,SC Davis, CJ Bernacchi, EH DeLucia. Heterotrophic respiration from soil increases with atmospheric carbon dioxide and temperature. Oral Presentation, Ecological Society of America Annual Meeting, Austin, TX, August 2011.

5. Publications

Manuscripts are current in progress but none have yet been submitted.

6. Student degrees supported

Two graduate students are funded through this grant. Both have finished two years of their Ph.D. studies.

Final Report

(4/30/2009-7/31/2012)
(Award Number DE-FC02-06ER64158)

Title: Partitioning responses of rhizosphere respiration and soil carbon decomposition to warming and altered precipitation in a grassland ecosystem

PI: Weixin Cheng, Environmental Studies, University of California, Santa Cruz, CA.
Collaborator: John Blair, Division of Biology, Kansas State University, Manhattan, KS.

1. Abstract

This research project primarily addresses the potential effect of root-soil interactions on the responses of soil organic carbon decomposition to warming and altered precipitation in a grassland ecosystem. Results from field experiment indicated that the impact of soil warming and altered timing of precipitation on soil CO_2 emissions varied depending on the seasonality. Soil warming generally enhanced total soil CO_2 efflux rate during the growing season, but only statistically significant during the fall season. Where as delayed precipitation generally reduced the contribution of root respiration to the total soil CO_2 emission, and concurrently enhanced CO_2 emission from microbial decomposition of soil organic carbon during the summer season. Results from lab-controlled experiments demonstrated that root-soil interactions strongly regulated the response of soil organic carbon decomposition to warming. Based on these findings we conclude that rhizosphere interactions crucially control soil decomposition processes and concurrently contribute to soil CO_2 emissions.

2. Research activities

Soil organic matter (SOM) decomposition releases a large amount of CO_2 from terrestrial ecosystems to the atmosphere, functioning as a major component of the global carbon cycle and greenhouse gas emissions. Therefore, how change of temperature and precipitation may influence SOM decomposition has been an issue of critical concerns. Given that SOM decomposition in virtually all terrestrial ecosystems always occurs with roots and rhizosphere priming effect, it is important to understand whether rhizosphere interactions alter the climatic effects on SOM decomposition.

The main objective of this project was to investigate both the heterotrophic and the autotrophic sources of soil CO_2 as they respond to warming and change of precipitation regimes at Konza Prairie grassland ecosystem. We proposed to test three hypotheses: **Hypothesis 1--** Warming a temperate grassland substantially intensifies the rhizosphere priming effect on soil organic matter (SOM) decomposition, thereby increasing the temperature sensitivity of overall CO_2 flux from heterotrophic respiration; **Hypothesis 2--**Prolonged drought periods without a change in total precipitation over the growing season reduce total belowground CO_2 efflux, primarily due to lower C input from reduced plant production/allocation and a lower level of rhizosphere priming effects on SOM decomposition; **Hypothesis 3--**The impacts of ecosystem warming and extended drought periods on autotrophic and heterotrophic belowground respiration are non-additive. We tested these hypotheses with a combination of field and lab experiments.

We established 16 field plots at the Konza Prairie rainfall manipulation (RaMPs) experimental site at the Konza Prairie Biological Station. These plots encompassed treatments of an ambient temperature and warming (infrared heating, +2ºC at 15 cm depth), an ambient precipitation and a delayed precipitation (prolonged drought) of lengthening the ambient dry intervals between rainfall events by 50%, with four replicates for each treatment. We first trenched around all plots and installed Zink-plated metal board and plastic liner. We cleared all existing vegetation and most plant roots from each plots and planted with a native C_3 grass (smooth brome, *Bromus inermis*) in June of 2009. The initial plant establishment was much slower than what we had expected due to its relatively low tolerance to late spring and summer heat. Because of the slow plant development, we prolonged the establishment period to the entire 2009 growing season, and started treatment manipulations and measurements at the beginning of the 2010 growing season. We also carried out experiments in a continuous ^{13}C-labeling growth chamber and a continuous ^{13}C-labeling greenhouse. Electrical heating devices were used in these lab experiments to achieve the warming manipulation.

3. Research highlights

The temperature sensitivity of SOM decomposition when planted with sunflower (*Helianthus annuus*) or soybean (*Glycine max*) was significantly higher than in the same soil when unplanted. Soil warming substantially intensified the rhizosphere priming effect on SOM decomposition (up to 3-fold increase by 5°C warming), thereby increasing the temperature sensitivity of overall soil heterotrophic respiration when roots and rhizosphere processes were active. These results from controlled growth chamber experiments demonstrated that root-soil interactions play a crucial role in shaping the temperature sensitivity of SOM decomposition (See publication of Zhu & Cheng 2011, Global Change Biology).

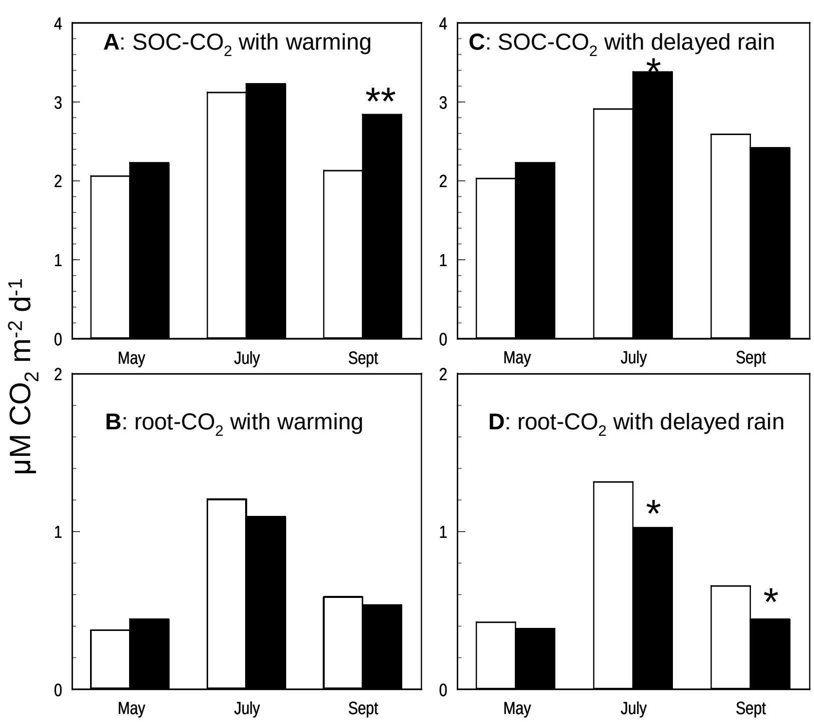

Figure 1. Soil CO_2 efflux originated from microbial decomposition of organic carbon (**A** & **C**) or from root/rhizosphere respiration (**B & D**) under the treatments of ambient temperature (unfilled bars in **A & B**) and warming (+2ºC at 15 cm depth, filled bars in **A & B**), and under the treatments of ambient precipitation (unfilled bars in **C & D**) and delayed precipitation (+50% of dry intervals, filled bars in **C & D**). ** and * indicate statistical significant differences between the ambient and the warming or the delayed precipitation treatments at P<0.05 and P<0.1 levels, respectively.

Soil warming (2ºC above the ambient at 15 cm soil depth) at the Konza tallgrass prairie site significantly enhanced the CO_2 efflux rate from soil organic carbon decomposition during the fall season, and did not significantly affect CO_2 efflux rate either from root/rhizosphere respiration or from soil organic carbon decomposition during other growing seasons. Delayed precipitation tended to reduce the contribution of root respiration to the total soil CO_2 emission, and concurrently enhanced CO_2 emission from microbial decomposition of soil organic carbon during the summer season (Figure 1, manuscript in preparation).

5. Publications

Publications supported by this grant funding (#DE-FC02-06ER64158):

Pausch, J., B. Zhu, Y. Kuzyakov, and W. Cheng. Plant inter-specific effects on rhizosphere priming of soil organic matter decomposition. Soil Biology & Biochemistry, in press.

Zhu, Biao, and Weixin Cheng. 2012. Nodulated soybean enhances rhizosphere priming effects on soil organic matter decomposition more than non-nodulated soybean. Soil Biology & Biochemistry 51: 56-65.

Zhu, B., and W. Cheng. 2011. Rhizosphere priming effect increases the temperature sensitivity of soil organic matter decomposition. Global Change Biology, 17: 2172-2183.

Zhu, B., and W. Cheng. 2011. ^{13}C isotope fractionation during rhizosphere respiration of C_3 and C_4 plants. Plant and Soil 342: 277-287

Zhu, B., and W. Cheng. 2011. Constant and diurnally-varying temperature regimes lead to different temperature sensitivities of soil organic carbon decomposition. Soil Biology and Biochemistry 43: 866-869.

Presentations in Scientific Meetings (supported by this grant funding: #DE-FC02-06ER64158):

Cheng, Weixin; Biao Zhu, and Feike Dijkstra. Reconcile box-arrow models with rhizosphere priming effect. Scaling Root Processes: Global Impacts Workshop, Washington DC. March 2012.

Cheng, Weixin. Rhizosphere priming effects on C and N mineralization: How much and so what? Emerging Frontiers in Rhizosphere Science Workshop, Sponsored by Soil Science Society of America and National Academy of Sciences, Washington DC, March 2011.

Pang , Xueyong, Biao Zhu, Xiaotao Lu, and Weixin Cheng. Substrate availability controls the temperature sensitivity of soil organic carbon decomposition: evidence from different soil depths. 96th Ecological Society of America Annual Meetings, Austin, Texas, August 2011.

Cheng, Weixin. The double agent of carbon input from roots: contribute to soil carbon and accelerate soil carbon loss through priming. Soil Science Society of America annual Meetings, Long Beach, CA, November 2010.

Cheng, Weixin. Root-Soil Interactions as Input-Driven Feedbacks in Regulating Soil Carbon Cycle. American Geophysical Union Fall Meetings, San Francisco, CA, December 2010.

Zhu, Biao, and W. Cheng. Root-soil interactions increase the temperature sensitivity of soil organic carbon decomposition through rhizosphere priming effect. Ecological Society of America Annual meetings, Pittsburgh, PA, August 2010.

Cheng, Weixin, Jessica Gutknecht, Daniel Keck, Biao Zhu. Rhizosphere Effects Reduce the Temperature Sensitivity of Soil Carbon Decomposition. American Geophysical Union Fall Meetings, San Francisco, CA, December 2009.

6. Student degrees supported:

Amy L. Concilio
PhD in Environmental Studies, University of California, Santa Cruz, CA, June 2012
Thesis Title: Cheatgrass invasion and global change in the eastern Sierra Nevada: Likelihood of spread and feasibility of control.

Biao Zhu
PhD in Environmental Studies, University of California, Santa Cruz, CA, September 2010
Thesis Title: Temperature control of rhizosphere priming effect on soil organic matter decomposition.

Project Report

Quantifying Carbon Cycle Partitioning During Climate Anomalies Using Atmospheric Carbonyl Sulfide (COS)

Prepared for:
Andrew Burton
Director of the Midwestern Regional Center
DOE National Institute for Climatic Change Research (NICCR)

January 2012

Submitted by:

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Project Duration: 1 year

Abstract:

The objective of this work was to quantify the net ecosystem exchange (NEE) flux partitioning into gross primary production (GPP) and respiration fluxes during recent Midwest carbon-climate anomalies using simulated and observed airborne measurements of carbonyl sulfide (COS) and CO_2. This objective addresses significant knowledge gaps for regional-scale assessments of carbon-climate feedbacks. Recent work suggests that a COS analysis provides a novel approach for estimating regional flux partitioning for North America. Atmospheric COS and CO_2 observations are useful for flux partitioning because regional gradients in atmospheric CO_2 are dominated by net ecosystem fluxes while regional gradients in atmospheric COS are dominated by GPP-related plant uptake. The scientific merit of the proposed work is a data-driven assessment of regional flux partitioning that is critical for exploring carbon-climate feedback mechanisms and lacking in existing techniques.

Research Activities:

The relative vertical gradients of NOAA/ESRL airborne observations in the Midwest growing season (2004-2008) were used to calculate the ratios of GPP to NEE as described in Campbell et al. [1]. While growing season COS gradients are dominated by plant uptake, the influence of anthropogenic, soil, and background variation was also accounted for using simulated COS concentrations and background site observations. Carbon-climate anomalies were identified using data from the USDA/NOAA/UNL Drought Monitor and CarbonTracker. The COS-based partitioning was compared with local AmeriFlux estimates and bottom-up estimates from a new COS-CO_2 version of the SiB land surface model through collaboration with Joe Berry (Carnegie Institution for Science) and Ian Baker (Colorado State University-Fort Collins). This work was completed in one year by the PI and one postdoc who was recruited and trained to complete this study (Mohammad Abu-Naser).

Results and Deliverables:

This study resulted in three deliverables including maps of the regional ratios of GPP to NEE, an analysis of how these ratios vary with carbon-climate anomalies, and a comparison of the regional partitioning based on the COS-CO_2 analysis, local eddy flux data, and terrestrial ecosystem models. These flux partitioning results show similarities between the seasonal trends in the top-down COS analysis that are relatively consistent with diagnostic ecosystem models but reveal errors in models driven by prognostic phenology. The COS-based flux partitioning was consistent with eddy-flux data in regions with relatively homogenous land-cover but differed for heterogenous landscapes. While the COS-analysis suggests a negative correlation between drought and the ratio of GPP to NEE, there was no clear trend in the ecosystem model and eddy flux data.

Broad Impacts:

These results were disseminated through 8 presentations in 2011 including an AGU session that the PI convened which was the first AGU session to focus on COS as a terrestrical ecosystem tracer. One paper is in review at Nature and one paper is in preparation February 2012 as the target submission date for the journal Biogeosciences. The results of this project provided the basis for a new modeling and field project that was funded by DOE/BER.

Results Highlights (unpublished an subject to revision):

The first objective was be quantify regional carbon flux partitioning based on airborne vertical profiles and atmospheric modeling. The ratio of GPP to NEE is proportional to COS-derived ecosystem-relative uptake (ERU). The observed ERU for NOAA/ESRL airborne observations were consistently lowest over the Midwest region suggesting a reduction in GPP to NEE ratios by greater than 50% relative to other North American regions (Fig. 1).

This observed trend was consistent for some but not all ecosystem models reviewed. Previous work normalizes these vertical gradients by the free troposphere concentrations. Here we normalize by surface layer observations to be consistent with COS-GPP parameterization developed from plant chamber experiments.

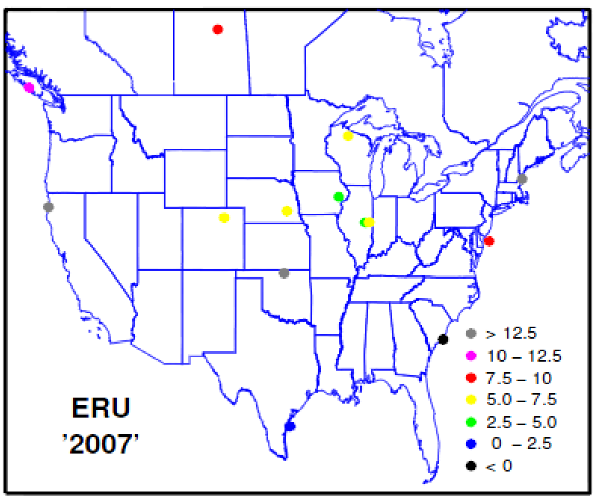

Figure 1. Ecosystem relative uptake (ERU) of COS to CO_2 from NOAA/ESRL observations. The ERU is the normalized vertical gradient of COS to CO_2.

The ERU is also sensitive to the leaf-scale relative uptake of COS to CO_2 which has been suggested to be different for C3 and C4 plants. However, recent plant chamber experiments suggest that this leaf-scale parameter is 36% lower for C4 plants relative to C3 plant which is not enough to explain the depressed ERU values over the midwestern region.

At most sites, the seasonal cycle showed strong similarities between COS vertical gradients and variations in fluxes from diagnostic ecosystem models (CASA and MODIS) and eddy flux data. The COS drawdown and GPP estimates for the ARM/Southern Great Planes site are plotted in Figure 2 which show GPP enhancement in the spring due to winter wheat crops and a fall peak due to weeds or cover crops. However the SiB ecosystem model did not capture these multiple peaks (Figure 3) which may be due to model parameterization in which CASA uses remotely-sensed phenology while recent SiB runs prognostic phenology (PGSI).

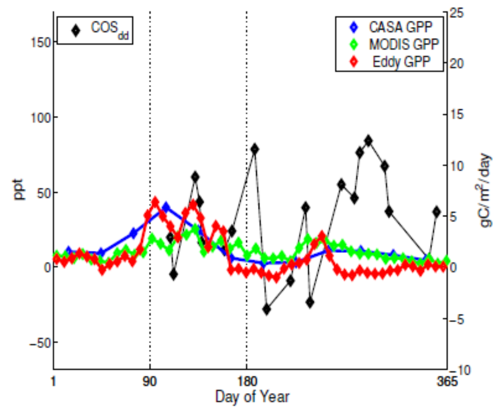

Figure 2. Seasonal variation at ARM Southern Great Planes site (OK) for COS airborne drawdown and GPP flux estimates from ecosystem model and eddy flux data in 2006.

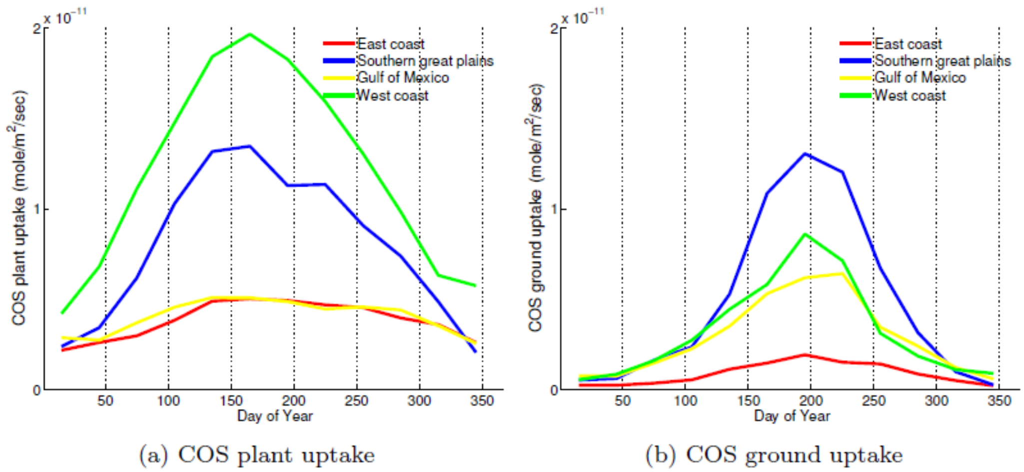

Figure 3. Seasonal variation for a mechanistic COS model developed for SiB including uptake by plants and soil.

The relationship between carbon flux partitioning and climate anomalies was explored through the relationship of ERU to drought index (Figure 4). Our composite drought index was negatively correlated with ERU at midwestern sites suggesting a reduction in the ratio of GPP to NEE for drought events. There was no consistent relationship between drought index and the GPP/NEE ratio for ecosystem model or eddy flux data.

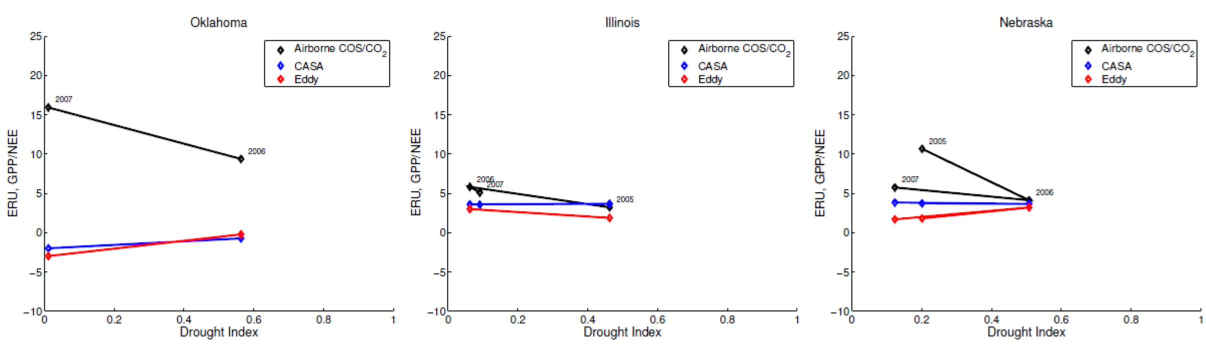

Figure 4. The relationship between drought index and carbon flux partitioning (ERU, GPP/NEE) from COS observations, ecosystem models, and eddy flux data.

Presentations

- Fall AGU 2011, Biogeosciences Section (2 oral, 1 poster), December 2011
- UC Santa Barbara, Bren School of Environmental Sciences & Management, October 2011
- University of Illinois, Urbana-Champaign, Department of Plant Biology, August 2011
- University of Sydney, Agriculture, Food and Natural Resources, July 2011
- Lawerence Livermore National Laboratory, Physical and Life Sciences, November 2011
- Stanford, Energy Resources Engineering, November 2011

Papers

- Campbell JE, Berry JA, Seibt U, Smith SJ, Montzka SA (In Review) "Enhanced gross primary production inferred from atmospheric carbonyl sulfide gradients", Nature
- Abu-Nasser M, Campbell JE, Berry JA, Baker I, Kawa R, Collatz J (In Preparation) Carbon cycle partitioning during North American climate anomalies using atmospheric carbonyl sulfide.

EXPERIMENTAL WARMING EFFECTS ON SOIL ORGANIC MATTER DYNAMICS AT THE TEMPERATE-BOREAL FOREST ECOTONE

Principal Investigator: Sarah E. Hobbie

Final Report
18 December 2011

1. ABSTRACT

Increased flux of CO_2 from terrestrial soils to the atmosphere in response to climate warming represents a potentially important positive feedback to climate change. Here, we aimed to combine measurements of *in situ* warming effects on soil respiration with mechanistic experiments to determine how the dynamics of warming effects on soil respiration are influenced by warming-induced changes in the soil microbial community; soil drying; and changes in decomposer use of labile versus recalcitrant soil organic matter (SOM) pools at the southern boreal-temperate forest ecotone. All major components of the proposed work have been completed, are in progress, or will be completed in 2012. Continued measurements of *in situ* soil respiration indicate that warming by 4°C has enhanced respiration by 18% and 25%, respectively, in 2009 and 2010. A set of three laboratory experiments were begun in 2011, that will help to elucidate the role of changes in the soil microbial community; carbon substrate depletion; and soil drying on soil microbial respiration (data are forthcoming).

2. RESEARCH ACTIVITIES

Location of Research Activities The funded research adds to an ongoing DOE-funded *in situ* warming experiment located at two sites just north of the southern boreal-temperate forest ecotone in northern Minnesota (CFC & HWRC; Fig 1). The experiment combines aboveground infra-red heating lamps with soil heating cables to increase air and soil temperature of replicated 3-m diameter plots by 2 and 4°C in both open and understory habitats at both sites. Treatments were initiated in April 2009

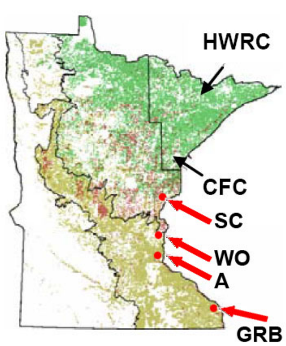

Figure 1. Location of study sites. The black arrows indicate the locations of the *in situ* warming experiments (at Hubacheck Wilderness Research Center (HWRC) and Cloquet Forestry Center (CFC) . The red dots and arrows (the four southern-most sites) indicate the locations of the *Aspen Temperature Gradient* sites. SC = St. Croix State Park, WO = William O'Brien State Park, A = Afton State Park, and GRB = Great River Bluffs State Park. Map colors indicate the pre-settlement distribution of all spruce (green), maples (red), and oaks (brown) in Minnesota. The spruce distribution closely matches the zone considered to represent boreal forest in the state.

Project Objectives We aim to combine measurements of *in situ* warming effects on soil respiration with mechanistic experiments to determine how the dynamics of warming effects on soil respiration are influenced by warming-induced phenotypic and genotypic changes in the soil microbial community; soil drying; and changes in microbial use of labile versus recalcitrant soil organic matter (SOM) pools at the southern boreal-temperate forest ecotone.

Specific Hypotheses: We hypothesized that warming will reduce the temperature sensitivity of microbial respiration over time by inducing both phenotypic and genotypic down-regulation (*hypothesis 1*), and result in soil drying that will inhibit soil respiration, offsetting, in part, the direct stimulating effects of warming on soil respiration (*hypothesis 2*).

In situ soil respiration (Hypothesis 1). *Methods applied***.** We have continued measurement of *in situ* soil respiration every 2 weeks during the warming treatment period (approximately April to November). We have 3 years of field data assessing the response of boreal forest soil respiration to warming.

Soil Incubations (Hypotheses 1 & 2):

Methods applied: In 2011, we began the 3 laboratory experiments proposed. Each experiment is planned to continue for one year, thus no data are available yet. The 3 experiments, however, have expanded in scale and scope from the original proposal.

Experiment 1: Temperature response with and without thermal Adjustment and soil drying on sieved soil. We established a laboratory soil incubation experiment to examine how microbial adjustment to warming and soil moisture content influences the temperature response of soil microbial respiration. Otherwise identical *sieved soils* from both of the experiment research sites (CFC and HWRC) have been incubated at either the mean growing season temperature of CFC (16°C) or at +4°C above mean growing season temperatures (20°C). Temperature response curves of respiration are being used to determine the response to warming for soils that differ in their potential temperature acclimation. Soil moisture was added as a variable (not originally proposed), in order to assess the effect of soil drying on the temperature sensitivity of respiration. This experiment is still in progress, and consists of 96 soil incubations [2 soil origins (Cloquet or Ely) x 2 temp (16°C or 20°C) x 3 soil moisture treatments x 8 replicates].

Experiment 2: Temperature response with and without thermal adjustment and soil drying on intact cores. This experiment is similar in methodology and scope to *Experiment 1*, except it uses *intact soil cores* (and not sieved soils) from both CFC and HWRC sites. Soil cores are 5.1-cm in diameter, taken from a depth of 0-10 cm, collected from both research sites (CFC & HWRC; Fig 1). This experiment is still in progress, and consists of 144 soil incubations [2 soil origins (Cloquet or Ely) x 2 canopy [forest or clearcut x 2 temp (16°C or 20°C) x 3 soil moisture treatments x 6 replicates]. Temperature response curves of respiration are being used to determine the response to warming for soils that differ in their potential temperature acclimation and soil moisture.

Independantly, *experiments 1 & 2* will illuminate the role of soil microbial thermal adjustment and soil moisture in influencing the temperature sensitivity of SOM decomposition to warming. Together, they will provide evidence for the interaction of soil structure with thermal adjustment and soil moisture content in controlling the temperature sensitivity of respiration.

Experiment 3: Temperature Response of Thermally Adapted Communities We are assessing the effects of genetic response to warming (i.e., thermally induced adaptation or community changes) on microbial respiration response to warming using incubations of sterilized soils that have been re-inoculated with microbial communities from similar forest types along a latitudinal temperature transect. (i.e. the Aspen Temperature Gradient; see Fig 1). We also used soil from the control and +4°C treatments in both of the DOE-funded *in situ* warming experimental sites in northern Minnesota (Fig. 1; CFC & HWRC) as inoculum sources (not originally proposed). In total, this experiment consists of 264 microcosms. 192 of these are sterile soil from one of the research sites (CFC or HWRC) that were re-inoculated with different microbial communites (2 sterilized soil origins [CFC and HWRC] x 8 inoculum x 6 replicates x 2 incubation temperatures). An additional 12 are control samples used to measure the sterilization effectively and contamination rate. The final 60 are control samples where we are measuring the respiration of each of the inoculum soils by itself. As in *experiments 1 & 2,* we are measuring temperature response curves of respiration in order to assess microbial community

3. RESEARCH HIGHLIGHTS

Currently, the data are available for *in situ* soil respiration in 2009 and 2010. Soil respiration data for the 2011 growing season is being processed, and will be available for analyses in early 2012. Preliminary data for the three lab soil incubations will be available in early 2012.

***Hypothesis 1*: Continued warming will reduce the temperature response of microbial respiration over time by inducing both phenotypic (acclimation) and genotypic (adaptation or community change) down-regulation by the microbial community.**

In situ experimental warming significantly enhanced soil respiration. Experimental warming increased soil CO_2 flux by 15% (2009) and 20% (2010) in the +4°C relative to the control at ambient temperature with inactive soil heating cables (Fig 2). In two years of soil respiration measurements there was no evidence for a diminishing response of soil respiration to temperature over time. *In situ* soil respiration in 2011 (and beyond), and the laboratory soil incubations in progress will be critical for understanding if the temperature response of microbial respiration shrinks over time

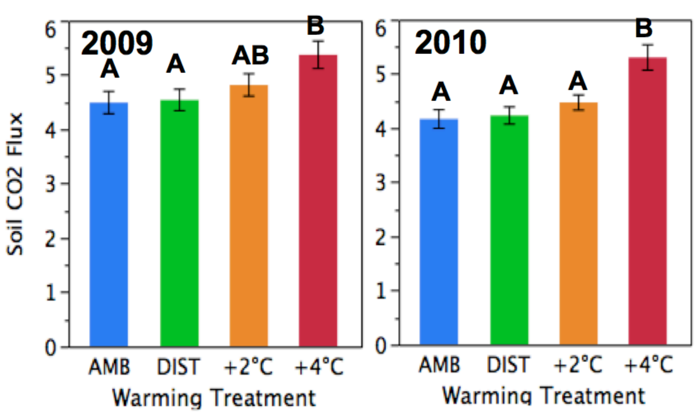

Figure 2. Warming treatments significantly increased soil respiration in both years. In 2009, soil respiration was 6% greater in the +2°C treatment, and 15% greater in the +4°C treatment relative to the ambient temperature, disturbed soil control. In 2010, soil respiration was 5% greater in the +2°C treatment, and 20% greater in the +4°C treatment.

***Hypothesis 2*: Warming will result in soil drying that will inhibit soil respiration, offsetting, in part, the stimulating effects of warming on soil respiration.**

Data are still forthcoming, but in progress.

4. RESEARCH PRODUCTS

Research Presentations:

Eddy, WC, SE Hobbie, PB Reich, R Rich, RA Montgomery, and J Oleksyn. Experimental Warming Effects on Soil Respiration at the Temperate Boreal Forest Ecotone. American Geophysical Union. 16 December 2010.

Eddy, WC, SE Hobbie, PB Reich, R Rich, RA Montgomery, and J Oleksyn. Experimental Warming Effects on Soil Respiration at the Temperate Boreal Forest Ecotone. Ecological Society of American. 3 August 2010.

5. PUBLICATIONS

Eddy WC, SE Hobbie, P Reich, R Rich, A Stefanski, and RA Montgomery. Experimental warming increases soil organic matter decomposition at the temperate-boreal forest ecotone. *Manuscript in Preparation for submission to Global Change Biology*

6. STUDENT DEGREES

The funded research contributed to training one graduate student (William Eddy). Anticipated graduate date is early 2013.

Controls on Soil Surface CO2, N2O and CH4 Fluxes, Ecosystem Respiration and Global Warming Potentials in Great Plains Agricultural Ecosystems

Principal Investigator: Timothy J. Arkebauer
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Objectives:

- Quantify soil surface fluxes of CO_2, N_2O and CH_4 through continuous (every 3 - 4 hours), year-round measurements in three maize and soybean agroecosystems

- Quantify ecosystem respiration using continuous soil surface CO_2 flux measurements and estimates of aboveground plant respiration

- Quantify global warming potentials using continuous soil surface CO_2, N_2O and CH_4 flux measurements

Approach:

At two of the three Nebraska AmeriFlux sites we have deployed continuous gas flux measurement systems based on vented, non-steady-state, flow-through (i.e., closed dynamic) sampling chambers (Livingston and Hutchinson, 1995). Similar systems have been used recently to continuously measure surface gas fluxes in other agricultural systems (e.g., Ambus and Robertson, 1998; Scott et al., 1999). Six chambers are connected, in turn, via a gas delivery system, to gas analyzers located in a central data collection/analysis hut. The chambers are equipped with closable tops (a "clamshell design") that are normally open. During the measurement period for a particular chamber, the top is closed and headspace air is circulated from the chamber to a gas chromatograph (GC-17A, Shimadzu, Inc.) for determination of CO_2, N_2O and CH_4 concentrations. We have also installed a small infrared gas analyzer (Li-820, Li-Cor, Inc.) in the airstream at each site to provide an additional CO_2 concentration measurement. The dimensions of the six rectangular chambers are about 0.43 m x 0.39 m x 0.18 m (height). The dimensions were chosen in order to reduce spatial variability in the flux measurements (Kaiser et al., 1996). We also desired to maximize chamber volume while minimizing the time the chamber must be closed in order to decrease adverse chamber influences on surface fluxes (Healy et al., 1996). The chambers are vented so as to reduce the effects of pressure differentials on surface fluxes (Fang and Moncrieff, 1998a; Lund, et al., 1999). Chambers have been placed in both "wheel track" rows and "non-wheel track" rows. All chambers are located within 50 m of the gas chromatograph and each chamber is sampled approximately every 3-4 hours. Throughout the design and construction phase of the project we worked in conjunction with colleagues at the University of New Hampshire (Dr. Patrick Crill's group).

The chamber areas are also located in close proximity to ongoing measurements of soil moisture and temperature profiles, belowground biomass, and ambient meteorological conditions being made by UNL Carbon Sequestration Project colleagues. Additional supporting measurements will also be made and two major efforts in particular must be highlighted. First, we will measure concentrations of trace gases in the soil atmosphere at several depths both underneath selected chambers and in non-chamber areas using techniques based on Fang and Moncrieff (1998b), Kammann et al., (2001) and Tang, et al., (2004). These profiles will aid in quantifying chamber effects on surface fluxes as well as elucidating mechanisms responsible for surface flux dynamics. Second, since soil moisture is a key edaphic parameter in controlling soil surface trace gas fluxes, and two of our three sites are irrigated via center pivots, we plan to install soil moisture sensors very close to the measurement chambers. Readings from these sensors will be monitored continuously with currently available dataloggers (CR-10X, Campbell Scientific, Inc.). In addition, we will determine key soil parameters (e.g., NO_3^- content, electrical conductivity, bulk density) near the chambers at regular (weekly, monthly) intervals.

In order to estimate the total respiratory exchange of CO_2 between the surface and the atmosphere, the respiration of aboveground plant parts must be added to the soil surface CO_2 fluxes discussed above. In this regard, we will continue to draw heavily on current research funded under the UNL Carbon Sequestration Project. In these studies, single leaf gas exchange properties are being quantified for each of the three maize and soybean agroecosystems. Responses of single leaf photosynthesis, stomatal conductance and respiration to environmental (light, temperature, vapor pressure deficit, CO_2 concentration) and biological (leaf N content, leaf age) controlling factors (e.g., Arkebauer, 1994) are being determined for maize and soybean. Field measurements are being made throughout the growing season using portable gas exchange systems (see Polley et al., 1992). In particular, steady-state responses of respiration to leaf temperature are being measured by enclosing leaves in opaque bags and monitoring CO_2 flux rates. Another critical factor controlling leaf respiration is the leaf nitrogen content. We are also determining the N status of plant tissues as part of the CSP experiment plan. Destructive samples of plant aboveground biomass are being taken periodically throughout the growing season for estimation of leaf area index. Subsequently, the biomass is separated into leaves, stems and reproductive parts and the N and C content determined.

We will consider making additional gas exchange measurements of other canopy elements such as stems and reproductive parts (e.g., tassels, ears, pods). These will be quantified in terms of biomass (i.e., mg CO_2 efflux per unit of dry mass) in order to take advantage of the aboveground biomass determinations of the CSP investigators.

We will quantify ecosystem respiration by summing the soil surface CO_2 flux measurements with the estimates of aboveground respiration. Strictly speaking, this estimate is applicable to the specific sites where the chamber and LAI measurements were made. However, in addition to this "point" estimate we desire to make spatially representative field-scale estimates in conjunction with the field-scale CO_2 flux measurements made using micrometeorological techniques. To this end, we have established (as part of the CSP studies) a series of six intensive measurement zones (IMZ) in each field. The locations of the IMZ were selected using fuzzy-k-means clustering (e.g., Dobermann and Oberthür, 1997) applied to seven layers of previously collected, spatially dense information (elevation, soil type, electrical conductivity, soil organic matter content, digital air photograph, NIR remote sensing, and four years of yield map data). The resulting locations represent all major occurrences of soil and crop production zones within the three sites. We have also mapped the spatial extent of each representative major soil and crop production zone within each site. We will utilize this information to provide field-scale estimates of ecosystem respiration and global warming potential.

First, we will use the LAI and aboveground biomass information from each IMZ to compute an aboveground respiration appropriate for a particular soil and crop production zone. The ground area covered by each production zone will be used to weight the contribution of each zone to the overall (field-scale) aboveground respiration. Next, we plan to make measurements of soil surface CO_2, N_2O and CH_4 fluxes, at regular intervals, within each of the production zones (i.e., at each IMZ). We are presently making these measurements for surface CO_2 fluxes using a dynamic chamber methodology (Rochette et al., 1991; Norman et al., 1992) and for surface N_2O and CH_4 fluxes (with CSP colleagues) using a static chamber approach (Mosier et al., 1991; Qian et al., 1997). The analyses of these fluxes will give us insight into how representative the continuous chamber measurements are relative to other locations in the field. We will utilize geostatistical approaches based on the IMZ classification to scale up the continuous chambers and weight the contribution of each IMZ to the total site estimate of surface CO_2, N_2O and CH_4 emissions.

Global warming potentials for each system will be based on estimates of net ecosystem carbon exchange plus annually integrated, spatially representative, surface fluxes of N_2O and CH_4. In addition, we will factor in the carbon costs of various agronomic inputs such as production costs of N fertilizer and lime applications, fuel used for crop management and irrigation, etc. (Robertson and Grace, 2004; Robertson, et al., 2000). Again, this work will be in conjunction with ongoing CSP activities where the full carbon costs of the three cropping systems are being studied. By using the continuous soil surface N_2O and CH_4 flux measurements proposed in this project we will therefore be able to extend the work we have begun as part of CSP and address a fuller suite of potential processes contributing to annual global warming potentials.

Results:

Carbon Dioxide Fluxes

Temporal variability in CO_2 fluxes was observed at diel and seasonal time scales. The chamber system had a system minimum detectable flux of 3.5 kg CO_2-C ha^{-1} d^{-1} (4.0 µg CO_2-C m^{-2} s^{-1}) for the irrigated maize and 4.7 kg CO_2-C ha^{-1} d^{-1} (5.4 µg CO2-C m-2 s-1) for rainfed maize-soybean.

The diel pattern of CO_2 flux indicated that maximum fluxes usually appeared in the late afternoon and minimum fluxes occurred in the early morning, under influence of soil temperature, soil water content and seasonal plant growth stage. Seasonally, CO_2 fluxes were relatively high during the growing season and low during the non-growing season, following the seasonal trends of soil temperature and growth of the plants. Fluxes reached a maximum of 85 kg CO_2-C ha^{-1} d^{-1} and 68 kg CO_2-C ha^{-1} d^{-1} around silking stage of maize for irrigated and rainfed site, respectively. Daily average CO_2 flux from the irrigated maize (≈ 38 kg CO_2-C ha^{-1} d^{-1}) was significantly larger than that from rainfed maize-soybean (≈ 22 kg CO_2-C ha^{-1} d^{-1}) probably due to large amount of residue, irrigation and N-fertilization events in the irrigated maize system. The fluxes in the soybean phase (≈ 26 kg CO_2-C ha^{-1} d^{-1}) of 2004 were smaller than in the maize phase (≈ 33 kg CO_2-C ha^{-1} d^{-1}) of 2005 for the rainfed maize-soybean rotation system. An annual estimated 10,800 kg CO_2-C ha^{-1} was emitted from the irrigated maize field and 5,700 kg CO_2-C ha^{-1} from the rainfed maize-soybean site. About 72% of the total annual CO_2 emissions occurred during the growing season from both sites.

Soil surface CO_2 flux is controlled by soil water content and temperature by affecting productivity of the cropping systems and decomposition rate of soil organic matter. An exponential relationship between soil CO_2 flux and soil temperature was observed over annual time scales, with Q_{10} values of 1.9 for the irrigated maize and 2.4 for the rainfed maize-soybean system. Higher CO_2 fluxes usually appeared when WFPS was about 55-60%. When WFPS was smaller than 55% or greater than 60%, CO_2 fluxes decreased. CO_2 fluxes are also strongly influenced by biotic factors especially during the growing season.

Nitrous Oxide Fluxes

Temporal variability in N_2O fluxes was observed at diel, seasonal and annual time scales. The diel pattern of N_2O flux indicates that maximum fluxes occur in late afternoon, mostly when N_2O fluxes were high during the growing season. No clear diel pattern was observed when either soil water or mineral N was limiting. Seasonal patterns showed that daily average N_2O fluxes ranged from -35 to 408 g N_2O-N ha^{-1} d^{-1} and from -5 to 176 g N_2O-N ha^{-1} d^{-1}, with median values of 34 and 28 g N_2O-N ha^{-1} d^{-1}, at the irrigated maize and rainfed soybean sites, respectively. N_2O fluxes varied widely throughout the year and exhibited dramatic, sharp peaks soon after each fertilizer application following irrigation or precipitation in the irrigated maize field. Pronounced N_2O flux peaks were not detected at the rainfed soybean site throughout the growing season of 2004, but were observed in the maize year of 2005 probably due to fertilizer application before planting. Annual N_2O emissions from the irrigated maize site (8.08 kg N_2O-N ha^{-1}) was about the same as that from the rainfed soybean site (8.61 kg N_2O-N ha^{-1}). They are both in the range of IPCC estimation of 0.95 – 8.5 kg N_2O-N ha^{-1} released from the irrigated maize system and 1.03 – 9.22 kg N_2O-N ha^{-1} from the rainfed maize-soybean rotation system, using IPCC default emission factor (EF) of 0.0125 ± 0.01 kg N_2O-N kg^{-1} N input.

Soil mineral nitrogen concentration (NH_4^+ and NO_3^-), water filled pore space (WFPS), and temperature are major driving factors for N_2O emissions by controlling microbial nitrification and denitrification. Large N_2O fluxes were observed at the irrigated maize during the growing season when WFPS was either less than 60% or greater than 60%, indicating that nitrification and denitrification could both be the responsible processes for N_2O production. N_2O fluxes increased with increasing WFPS when WFPS was greater than 60%, implying that denitrification was the major source of N_2O production under anaerobic conditions. Similar relationships between N_2O flux and WFPS were less marked at the rainfed maize-soybean site, probably attributed to lower N availability and lower WFPS during the growing season. During the non-growing season, no clear relationships were observed at either site although WFPS was high, likely due to low temperatures and low NO_3^--N concentrations (4.06 - 4.18 mg kg^{-1} for the irrigated site and 2.41 - 3.38 mg kg^{-1} for the rainfed site). N_2O fluxes increased with increasing soil temperature when soil water content and mineral N were not limiting.

Methane Fluxes

Temporal variability in CH_4 fluxes was observed by our automated closed-chamber system at diel, seasonal and annual time scales. The diel pattern of CH_4 flux from the irrigated maize field indicated that CH_4 was either taken up by soils or emitted from the soil to the atmosphere, with the maximum rates appearing in the afternoon or at night. CH_4 fluxes mostly shifted around zero over 24-hour time period, with maximum emission rates typically occurring at noon or night and maximum uptake rates appearing in the afternoon or early morning.

Positive higher CH_4 fluxes appeared in the temperature range of 0-15 ^oC when soil WFPS was usually above 65%, while negative higher fluxes were in 15-28 ^oC when soil WFPS was typically from 40-60%. This implies that microbial process of methanogenesis responsible for CH_4 production is prevailing in temperature range of 0-15 ^oC, while methanotrophy responsible for CH_4 oxidation is predominant in temperature range of 15-28 ^oC under adequate water conditions. Higher CH_4 fluxes usually appeared when WFPS was greater than 65% and soils were under anaerobic conditions where microbial processes of methanogenesis for CH_4 production prevailed; and CH_4 fluxes were usually negative at both sites when WFPS was smaller than 65% and soils were under aerobic conditions where methanotrophy for CH_4 oxidation predominates.

The seasonal patterns showed that daily average CH_4 fluxes didn't vary widely, typically in the range from -30 to 60 g CH_4-C ha^{-1} d^{-1} for the irrigated maize, except that higher CH_4 fluxes were observed at the irrigated maize field in the 2004 growing season. CH_4 fluxes at the rainfed maize-soybean field were ranged from -10 to 60 g CH_4-C ha^{-1} d^{-1}, slightly smaller in magnitude than that at the irrigated maize site, and the fluxes in the soybean phase of 2004 were smaller than in the maize phase of 2005.

An estimated 422 g CH_4-C ha^{-1} was emitted annually from the irrigated maize field and 190 g CH_4-C ha^{-1} from the rainfed soybean site. Soils are either a minor CH_4 emitter or a small sink for atmospheric CH_4, which could be influenced by the management practices such as irrigation and N-fertilization. During the growing seasons, CH_4 fluxes were negative at both sites, indicating that atmospheric CH_4 was taken up by the soils and the soils acted as net sinks of methane. During the non-growing season, the soils of both sites were net sources of methane.

Global Warming Potentials

Significant net biome production (≈ 148 g C m^{-2} yr^{-1}) existed in the rainfed maize-soybean rotation system when it was in the maize phase in 2005, owing to greater annual NEE and less grain removal in harvest. In contrast, the irrigated maize system was a net source of C with loss of 88 to 108 g C m^{-2} in 2005, due to smaller NEE, larger amount of grain removal during harvest and CO_2 emissions from irrigation water.
The GWP was estimated using IPCC (2007) 20-year and 100-year time horizon factors for N_2O and CH_4, with consideration of the annual site C balance and production C-cost. The irrigated maize system was a net source of GHG, with an annual estimate of about 1100 g CO_2-equivalents m^{-2}, among which about half was contributed by N_2O flux, and 30% from site C balance. The rainfed maize, in contrast, had a mitigation potential of about 60 g CO_2-equivalents m^{-2} owing to a high rate of site C balance, and lower rates of N_2O and CH_4 flux and production C-costs. Contribution of CH_4 flux was small and negligible for both systems. Management strategies in agricultural ecosystems should be made for improving crop production but also reducing GWP by maximizing crop yield potential, biomass productivity and residue inputs and improving water and N use efficiencies.

Future research should concentrate on (i) determining spatial variability in N_2O flux to reduce the uncertainty in GWP estimate at the field-scale; (ii) demonstrating the potential impact of management practices at production scale, particularly to determine whether it is possible to reduce the large seasonal fluctuations in N_2O and CO_2 emissions from the soil surface; (iii) estimating the mitigation potential of the harvested grain as used for biofuel production for offsetting the C costs of production inputs.

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Post-doctoral Researcher Supported:

Brigid Amos, University of Nebraska-Lincoln

Graduate Student Supported:

Hui Shen, Beijing, China, University of Nebraska – Lincoln, Ph.D. (August 2008)

There were no patents resulting from the research. There was no equipment nor property bought with the research funds.

Final Technical Report
National Institute for Global Environmental Change

Project Title:
Evaluating changes in soil carbon cycling in reed canary grass invaded soils subject to elevated atmospheric CO_2 and increased soil nitrogen

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Abstract:

Invasion by reed canary grass (*Phalaris arundinacea*), rising atmospheric CO_2 levels, and altered soil nitrogen availability are important factors affecting ecosystems in the Midwestern U.S. The overarching goal of the research proposed here is to increase our understanding of mechanisms controlling C-storage under long-term environmental change. In particular, we asked why and how does carbon utilization by microorganisms change in the face of elevated CO_2, N availability, and invasion by exotic plant species? We found in Kao-Kniffin and Balser (2007) that an enriched atmosphere of CO_2 does not have visible effects on aboveground plant biomass, but instead resulted in large impacts belowground. We found that changes in the relative abundance of lipid indicators that are thought to represent gram-negative and gram-positive bacteria could affect the rate of carbon cycling in soils exposed to different global change scenarios (invasion, CO_2 enrichment, and nitrogen inputs). An additional experiment conducted in a sedge meadow showed that reed canary grass invasion has the potential to slow down the rate of N and C cycling by shifting soil microbial community structure to favor the growth of slower-growing gram-positive bacteria (Kao-Kniffin and Balser, *In revision*). Forthcoming results on a litter decomposition and carbon storage experiment will provide more insights on the impact of invasive species on soil carbon cycling, and will be used to develop management strategies for reed canary grass.

Research Activities

Summary of the project objectives.

(1) Quantify changes in rhizosphere and bulk soil microbial community structure from soil dominated by reed canary grass and native vegetation, exposed to elevated and ambient CO_2 and differing nitrogen concentrations (in controlled greenhouse facility).

(2) Quantify differences in decomposition (litter mass loss, enzyme activity, incorporation into microbial biomass) of invasive and native species litter grown under elevated and ambient CO_2 concentrations.

(3) Estimate changes in carbon cycle pools and fluxes (total carbon, dissolved organic carbon, microbial biomass carbon) associated with microbial community shifts.

Approach:

A variety of methods were used throughout the project to elucidate the role of soil microorganisms in carbon cycling in response to global change:

Microbial lipid analysis

Individual fatty acids are found in the membranes of nearly all microorganisms, but because the relative amount of each fatty acid varies among organism groups, lipid profiles are useful in determining the presence and relative abundance of general (functional) groups of organisms in soil. The assay is based on a modified Bligh-Dyer procedure described in Kao-Kniffin and Balser (2007). We used a hybrid procedure of phospholipid fatty acid (PLFA) and fatty acid methyl ester (FAME) to analyze microbial community composition. The procedure is based on the extraction of 'signature' lipid biomarkers from soil organisms (White and Ringelberg, 1998). The soil samples were homogenized, frozen, and lyophilized before lipid extraction. All glassware was baked at 550oC for 3 hr, and all Teflon or Teflon-lined caps were hexane-rinsed before the analysis. The lipids were extracted and purified using steps from a modified Bligh and Dyer (1959) technique for PLFA extraction, combined with FAME as described by Microbial ID Inc. (Hayward, CA). We extracted lipids from 3 g of freeze-dried soil using a chloroform-methanol extraction with a phosphate buffer [potassium phosphate, 0.1 M and pH 7 (3.6 ml), methanol (8 ml), and $CHCl_3$ (4 ml)] in 25-ml glass tubes, shaken for 1 hr and centrifuged. Supernatant was then decanted to 30 ml Teflon tubes, potassium phosphate buffer and $CHCl_3$ were re-added, and the tubes were vortexed for 30 sec. The phases were allowed to separate overnight at room temperature. The top layer was aspirated off (saving the chloroform phase), and volume was reduced in a RapidVap. We then followed the procedure for FAME as given by Microbial ID Inc.; sodium hydroxide is added for saponification and the solution heated in a water bath for 30 minutes, followed by methanolysis.

A 2 µl injection of the methyl-ester derivatives of the extracted lipid was analyzed using a Hewlett-Packard 6890 Gas Chromatograph equipped with a flame ionization detector and split/splitless inlet and a 25 m x 0.2 mm inside diameter x 0.33 µm film thickness Ultra 2 (5%-phenyl, 95% methyl) capillary column (Agilent) using hydrogen as the carrier gas, N as the make up gas, and air to support the flame. Gas chromatograph conditions are set by the MIDI Sherlock program (MIDI, Inc. Newark, DE). Peaks were identified with bacterial fatty acid standards and Sherlock peak identification software (MIDI, Inc. Newark, DE). Fatty acids were quantified by comparisons of peak areas from the sample compared to peak areas of two internal standards, 9:0 (nonanoic methyl ester) and 19:0 (nonadeconoic methyl ester), of known concentration. In all subsequent analyses we used only fatty acids that were identifiable and present at >0.5 mol percent.

Lipids cannot confidently be used to represent specific strains or species but are more commonly assigned to ecological guilds. Terminology to describe fatty acids is described by 'A:BwC' where 'A' indicates the total number of C atoms, 'B' the number of double bonds (unsaturations), and 'w' indicates the position of the double bond from the methyl end of the molecule. The prefixes 'i' and 'a' refer to iso and anti-iso methyl branching. Monounsaturated fatty acids labeled with a 'c' or 't' refer to cis or trans forms. Hydroxy groups are indicated by 'OH'. Cyclopropyl groups are denoted by 'cy' (Arao, 1999; Bååth and Anderson, 2003; Steenwerth et al., 2003).

Enzyme Activity Assays: Assays for enzyme activity in soils can be useful in providing functional comparisons of microbial communities (Saiya-Cork et al. 2002). The activities of eight enzymes associated with C, N, and P cycling and litter decomposition were measured: acid and alkaline phosphatase, ß-1,4-glucosidase, ß-1,4-N-acetylglucosaminidase, L-leucine aminopeptidase, ß-1,4 xylosidase, phenol oxidase, and peroxidase. One g of homogenized soil will be added to 125 ml of 50 mM acetate buffer at pH 5.0. Aliquots (200 µl) of the slurry mixture will be placed into 96-well microtiter plates. We will have 16 replicate wells per sample per plate and 8 replicate wells per sample control (50 µl of buffer plus 200µl of sample suspension), substrate control (50 µl of substrate solution plus 200 µl of buffer), and quench standard (50 µl of standard plus 200 µl of sample suspension). The plates will be incubated in the dark for 3 hours at 24°C. A 10 µl aliquot of 1.0 M NaOH will be added to each well in order to terminate the reaction and develop color in the wells. Fluorescence will be measured using the Fluorolite 1000 (Dynatech Laboratories), set at 365 nm excitation and 450 nm emission filters. Phenol oxidase and peroxidase activities will be measured using the MRX spectrophotometer (Dynatech Laboratories) set at 450 nm. For phenol oxidase, 50 µl of 25 mM L-3,4-dihydroxyphenylalanine (DOPA) will be added to each sample well, whereas for peroxidase, 50 µl of 25 mM DOPA plus 10µl of 0.3% H_2O_2. Controls and replicates were processed similarly as in the pNP method. All enzyme activities will be reported as $\mu mol \cdot h^{-1} \cdot g^{-1}$ organic matter or dry mass of soil.

Gross nitrogen transformation

The ^{15}N isotope dilution method provides an estimation of gross rates of N mineralization occurring at the field sites (Hart et al 1994). For each location and vegetation type, four replicate PVC tubes (9 cm long and 5 cm diameter) were pounded into the soil and removed. The soil within the cores was labeled with 99% ^{15}N as $(^{15}NH_4)_2SO_4$ using a spinal needle. Two of the cores were placed back into the soil, while the other two cores were taken back to lab and immediately processed for initial N readings. Soil from the cores was homogenized and extracted in 2 M KCl to determine initial pool sizes of N and their initial atom % ^{15}N enrichments and recovery. The samples were shaken for 2 hr and filtered through pre-leached Whatman no. 42 filters for NH_4^+-N analysis on an automatic flow-injection analyzer (Lachat Instruments, Loveland, CO). After field incubation in the soil for 24 hr, the other half of the cores were retrieved and processed similarly to the initial samples to determine dilution rates. Approximately 25 ml of the KCl extracts were placed into specimen cups. Filter disks saturated with KHSO4 were suspended above the extracts using wire. MgO was immediately added to the extract and the cups were sealed for six days. The disks were then dried overnight in a desiccator lined with concentrated sulfuric acid, and placed into tin (Sn) 8x5 mm capsules for direct combustion ^{15}N analysis. The samples were processed at the UC Davis Stable Isotope Facility on an isotope-ratio mass spectrometer (PDZ Europa Inc.) for atom % ^{15}N enrichment. Gross rates of mineralization were calculated from the dilution of the $^{15}NH_4^+$ pools between the initial and final time points.

General soil analysis (N and P extracts, total C and N, SOM, pH, and soil water content:

Soil NH_4^+, NO_3^-, and inorganic P were determined by extraction of soil samples with either 0.5 M K_2SO_4 or 0.5 M $NaHCO_3$. The samples was shaken for 2 hr and filtered through pre-leached Whatman no. 42 filters. The samples were analyzed using a Lachat automatic flow-injection analyzer (Lachat Instruments, Loveland, CO). Total C and N were determined using sieved and homogenized soil that was dried for 48 hr at 70 °C. The dried soil was ground using a mortar and pestle and analyzed using the CNS elemental analyzer (Leco Corp.). Soil organic matter content was determined by mass loss-on-ignition at 550 °C. Soil pH was measured by electrode in a 1:2 ratio of soil in 0.01 M $CaCl_2$. Gravimetric soil water content for all soil analyses was determined after 2 days at 105°C.

Research Highlights

Results from:

Kao-Kniffin, J. T. and T.C. Balser (2007), **Elevated CO_2 differentially alters belowground plant and soil microbial community structure in reed canary grass-invaded experimental wetlands**, *Soil Biology & Biochemistry*, *39*, 517-525.

Several recent studies have indicated that an enriched atmosphere of carbon dioxide (CO_2) could exacerbate the intensity of plant invasions within natural ecosystems, but little is known of how rising CO_2 impacts the belowground characteristics of these invaded systems. In this study, we examined the effects of elevated CO_2 and nitrogen (N) inputs on plant and soil microbial community characteristics of plant communities invaded by reed canary grass, *Phalaris arundinacea* L. We grew the invasive grass under two levels of invasion: the invader was either dominant (high invasion) at >90% plant cover or sub-dominant (low invasion) at <50% plant cover. Experimental wetland communities were grown for 4 months in greenhouses that received either 600 µl l^{-1} or 365 µl l^{-1} (ambient) CO_2. Within each of 3 replicate rooms per CO_2 treatment, the plant communities were grown under high (30 mg l^{-1}) or low (5 mg l^{-1}) N. In contrast to what is

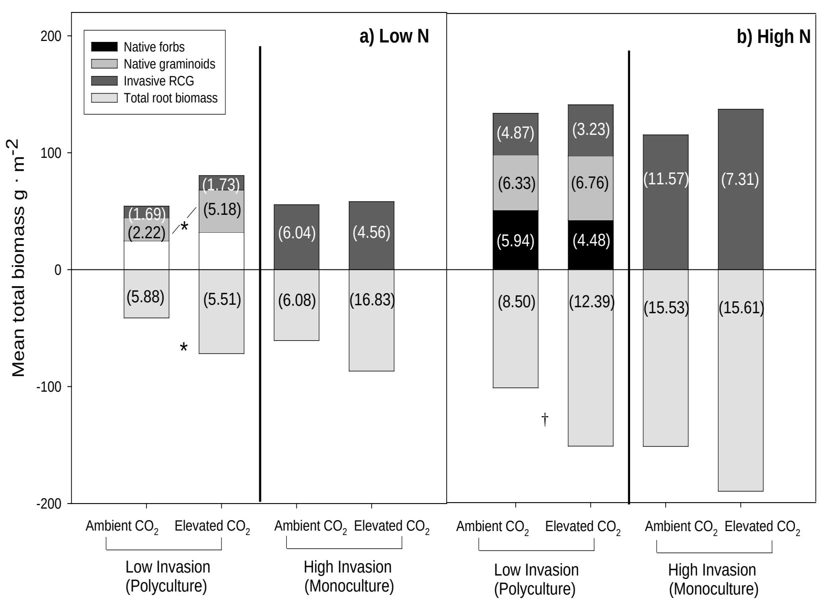

Figure 1: Effects of elevated CO_2 on plant aboveground and belowground biomass (g) in high invasion (monoculture) and low invasion (polyculture) communities grown under a) low N and b) high N. Asterisk (*) indicates significance at $P<0.05$ and dagger (†) indicates significance at P<0.1 (Fisher's LSD) for total aboveground biomass, native graminoids biomass, and total belowground biomass. Standard errors are located on the bars within parentheses.

Table 1
Effects of elevated CO_2 on relative abundance in mol% of microbial lipid indicators under ambient and elevated CO_2, low and high N inputs, and low and high invasion by reed canary grass

Lipids	Low invasion (Polyculture)				High invasion (Monoculture)			
	Low nitrogen		High nitrogen		Low nitrogen		High nitrogen	
	Amb. CO_2	Elev. CO_2	Amb. CO_2	Elev. CO_2	Amb. CO_2	Elev. CO_2	Amb. CO_2	Elev. CO_2
Saturated								
12:0	0.89 (0.06)	1.05 (0.05)	0.81 (0.05)	1.14 (0.05)	0.88 (0.08)†	1.20 (0.19)†	0.73 (0.08)***	1.06 (0.10)***
14:0	3.05 (0.13)	3.70 (0.13)	2.78 (0.12)	3.59 (0.10)	3.03 (0.14)**	2.96 (0.47)**	2.75 (0.10)***	3.29 (0.11)***
20:0	1.75 (0.09)	2.03 (0.09)	1.53 (0.14)	2.15 (0.08)	1.82 (0.12)***	2.38 (0.20)***	1.57 (0.10)***	2.06 (0.09)***
Monounsaturated								
17:1w7c	0.11 (0.08)†	0.28 (0.11)†	0.06 (0.06)**	0.30 (0.11)**	0.00	0.24 (0.11)	0.04 (0.04)	0.43 (0.02)
18:1w7c	0.90 (0.06)	0.72 (0.04)	0.98 (0.05)	0.70 (0.04)	0.96 (0.09)**	0.84 (0.04)**	1.06 (0.12)***	0.80 (0.04)***
19:1w8t	3.48 (0.30)	3.97 (0.22)	2.82 (0.29)	4.21 (0.15)	3.35 (0.34)	4.66 (0.36)	2.88 (0.23)**	3.90 (0.21)***
Hydroxy								
18:02OH	1.14 (0.07)*	1.23 (0.05)*	1.05 (0.07)	1.31 (0.04)	1.07 (0.09)	1.52 (0.13)	0.95 (0.06)	1.21 (0.05)
Cyclo								
cy19:0	2.19 (0.08)	2.32 (0.10)	2.09 (0.11)	2.53 (0.10)	2.19 (0.12)†	2.72 (0.26)†	1.97 (0.09)***	2.26 (0.08)***

Asterisk (*) indicates significance at $P<0.05$, (**) at $P<0.01$, (***) at $P<0.001$, and dagger (†) indicates significance at $P<0.1$ (Fisher's LSD). Error bars are ±1 SE of the mean ($n = 15$).

often predicted under N limitation, we found that elevated CO_2 increased native graminoid biomass N, but not at high N (Fig. 1). The aboveground biomass of reed canary grass did not respond to elevated CO_2, despite it being a fast-growing C3 species. Although elevated CO_2 had no impact on plant biomass of heavily invaded communities, the relative abundance of several soil microbial indicators increased (Table 1). In contrast, the moderately invaded plant communities displayed increased total root biomass under elevated CO_2, little impact occurred on the relative abundance of microbial indicators. Principal components analysis indicated that overall soil microbial community structure was distinct by CO_2 level for the varying invasion treatments (Fig. 2). This study demonstrates that even when elevated CO_2 does have visible effects on aboveground plant biomass, have large impacts belowground.

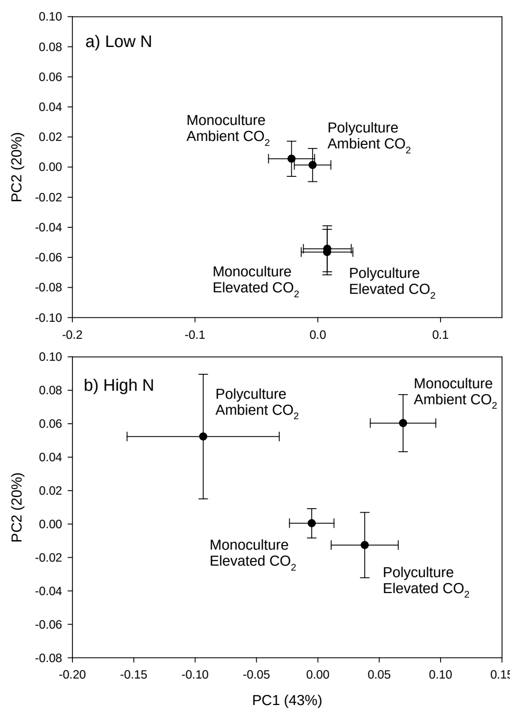

Figure 2: Principal components analysis of microbial lipids from elevated vs. ambient CO_2 and low (polyculture) vs. high (monoculture) invasion treatments under: a) low N and b) high N. Error bars are ± 1 SE of the mean (n = 15). The first and second principal components account for 63% of the variability.

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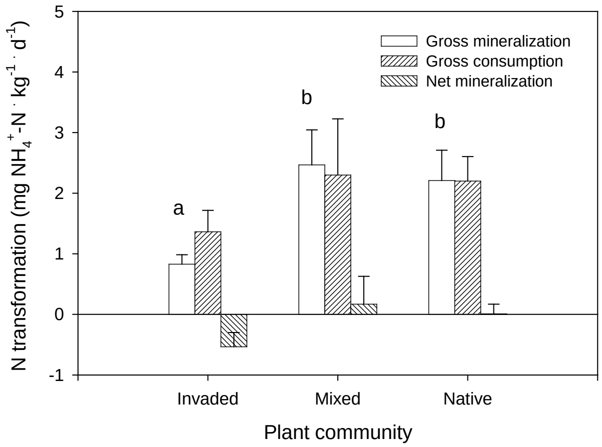
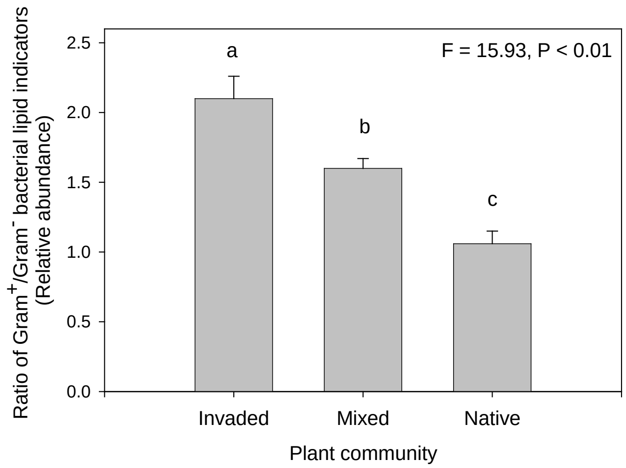
Results from:
Kao-Kniffin, J. T. and T.C. Balser (*In review*), **Reed canary grass invasion decreases N mineralization and shifts microbial community towards slower N and C**





cycling bacteria, *Restoration Ecology*.

Reed canary grass (*Phalaris arundinacea* L.) is among the most noxious invaders of wetlands across North America. Several researchers have documented the loss of biodiversity associated with reed canary grass expansion, but few studies have elucidated the impacts of the species on ecosystem functioning. Gross nitrogen (N) mineralization rates, extractable N pools, and soil microbial community structure were measured from replicated plots dominated by reed canary grass (invaded), co-dominated by reed canary grass and native plants (mixed), or dominated by native plants with reed canary grass excluded (native). Communities invaded by reed canary grass showed a reduction in N mineralization rates, compared to the native and mixed plant communities (Fig. 3). Soil extractable NH_4^+-N and NO_3^--N levels did not differ among the plant communities, despite the higher biomass associated with reed canary grass invaded sites. Microbial lipid analysis revealed that overall microbial community structure in native plant communities differed significantly from the invaded and mixed communities. Invasion by reed canary grass led to a shift in the relative abundance of monounsaturated lipids (gram-negative bacterial indicator) to branched chain lipids (gram-positive bacterial indicator) (Fig. 4). In effect, invasion has shifted the soil microbial community towards slower-growing bacteria that tend to specialize on more complex carbon (C) substrates. The shift in microbial ecological niches is consistent with the decrease in N mineralization rates in invaded soils. The results from this study show that reed canary grass invasion into native plant communities has the

Figure 3. Gross and net N transformations in soils collected from invaded (n=8), mixed (n=6), and native (n=8) plant communities using ^{15}N isotope dilution (means ±1 SE). Bars showing different letters indicate significantly different means at P < 0.05 (Fisher's LSD) for gross mineralization. There were no significant differences in the means of gross consumption or net mineralization rates under the different plant communities.

Figure 4. Ratio of gram-positive:gram-negative bacterial lipid indicators from soils collected in invaded (n=4), mixed (n=3), and native (n=4) plant communities (means ±1 SE). Bars showing different letters indicate significantly different means at P < 0.05 (Fisher's LSD).

Kao-Kniffin, J., D. Freyre, T.C. Balser. 200x. In revision. The link between elevated CO2 and increased methane emissions: Does plant or microbial composition matter? Intended for *Global Change Biology*

Kao-Kniffin, J. T. and T.C. Balser (*In review*), Reed canary grass invasion decreases N mineralization and shifts microbial community towards slower N and C cycling bacteria, *Restoration Ecology*.

Kao-Kniffin, J. T. and T.C. Balser (2007), Elevated CO_2 differentially alters belowground plant and soil microbial community structure in reed canary grass-invaded experimental wetlands, *Soil Biology & Biochemistry*, *39*, 517-525.

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Kao-Kniffin, J. T. and T.C. Balser (2007), Elevated CO_2 differentially alters belowground plant and soil microbial community structure in reed canary grass-invaded experimental wetlands, *Soil Biology & Biochemistry*, *39*, 517-525.

Kao-Kniffin, J. T. and T.C. Balser (In preparation), Reed canary grass invasion decreases N mineralization and shifts microbial community towards slower N and C cycling bacteria, Intended for *Ecological Applications*.

Steenwerth, K. L., L. E. Jackson, F. J. Calderón, M. R., Stromberg, and K. M. Scow (2003), Soil microbial community composition and land use history in cultivated and grassland ecosystems of coastal California, *Soil Biology & Biochemistry*, 35, 489-500.

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Students:

Name	University, City, State	% Time on Project	Degrees received during project, AY received	Congressional District
Kao-Kniffin, Jenny	University of Wisconsin, Madison, WI	%50	Ph.D., 2007	2
Santana, Mirna	University of Wisconsin, Madison, WI	%10	Ph.D. candidate	2
Freyre, Dominique	University of Wisconsin, Stevens Point , WI	%10	B.S., 2006	7
Dobrient, Marlo	University of Wisconsin, Madison, WI	%15	B.S., 2006	2
Faust, Katherine	University of Wisconsin, Madison, WI	%15	B.S., 2007	2
Chiang, Vivian	University of Wisconsin, Madison, WI	%5	B.S., 2007	2

Final Report
Midwestern Regional Center of the Department of Energy's National Institute for Climatic Change Research

Project Title:
Effects of Altered Rainfall Timing and Warming on Soil and Plant Responses in a Grassland Ecosystem

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1. Abstract.

Temperature and rainfall are critical drivers of ecological processes in grasslands. In the Central Plains mean temperatures are expected to increase and rainfall patterns are predicted to become more variable and extreme, with increased frequency of large rainfall events and extended inter-rainfall droughts. We addressed the consequences of these changes using field-scale rainfall manipulation plots to alter the timing of growing season rainfall and increase temperature in intact grassland ecosystems. Our central hypothesis was that changes in the timing of rainfall events (larger events with longer inter-rainfall droughts, but no change in total precipitation amount) will alter temporal and spatial soil moisture dynamics, with long-term consequences for soil, plant, community and ecosystem processes. We expected complex interactions between altered rainfall timing and warming. Results to date indicate significant reductions in both plant productivity and soil respiration with more extreme rainfall patterns, and increased potential for N losses. Warming exacerbated the negative effects of altered rainfall timing on plant productivity and soil respiration, presumably due to increased water limitations with elevated temperature. Understanding the interactive effects of more extreme rainfall patterns and warmer temperatures will be critical for predicting the sustainability of grassland resources and ecosystem services under a future climate.

2. Research activities

Our objectives were (1) to determine how above- and belowground ecosystem processes respond to increases in ambient temperature and more extreme patterns of precipitation, and (2) to identify the potential consequences of these responses for grassland ecosystem function under an altered climate. To address these objectives, we expanded and continued a long-term field experiment in which the timing of rainfall events and temperature are simultaneously manipulated in native grassland. Our central hypothesis was that changes in the timing of rainfall events, as predicted by GCMs, and increases in mean temperature will significantly alter temporal patterns and depth distributions of soil moisture and, consequently, key above- and belowground processes, including plant productivity, soil respiration, soil nutrient availability and root dynamics. Understanding these responses will be critical for explaining and predicting changes in the structure and functioning of grassland ecosystems under a more variable future climate. Specific objectives included:

- determining how altered patterns of growing season precipitation and increased temperatures affect aboveground plant productivity (ANPP).
- quantifying how key soil processes, including soil CO_2 flux and nitrogen transformations (N availability and potential for loss), respond to altered patterns of growing season precipitation and increased temperature.
- determining how altered patterns of growing season precipitation and increased temperatures affect belowground plant processes, including allocation to root biomass, root tissue chemistry and the turnover of fine roots.
- evaluating the ecosystem-level consequences (i.e., soil organic matter storage and turnover, nutrient cycling processes, primary productivity) of soil and plant responses to altered rainfall and temperature regimes.

This ongoing experiment is being conducted at the Konza Prairie Biological Station (KPBS), a 3487-ha tallgrass prairie, which is a part of the NSF Long-Term Ecological Research network. The tallgrass prairie is a highly productive grassland, of significant agricultural and economic importance to the U.S. It is also particularly appropriate for addressing climate change studies because production responses to climate variability are large (up to 4-fold from dry to wet years), and water availability plays an important role in regulating soil processes and soil communities. Our approach for studying potential impacts of climate change in these grasslands has been to experimentally manipulate rainfall patterns and temperature in native grassland plots under realistic field conditions. We use modified rainout shelters which exclude rainfall from 7.6 x 7.6 m experimental plots and allow us to reapply natural rainfall as dictated by our experimental protocol (Fig. 1). These Rainfall Manipulation Plots (RaMPs) allow us to manipulate both the amount and the temporal variability in rainfall reaching the plots. The RaMPs have clear plastic roofs, which divert natural rainfall into two 4000 L reservoirs capable of storing 10 cm of rain. The rain is reapplied using an overhead sprinkler system. In spring 2003, we installed two 4-m^2 temperature manipulation plots in each RaMP (and each non-sheltered reference plot), modifying the experiment to a split-plot design, with precipitation as the whole-plot treatment and warming as the subplot treatment (Fig. 1). Thus, we altered rainfall timing while assessing the impacts of increased temperature, as well as their interactive effects, on this grassland ecosystem. Treatments are currently implemented as follows:

Ambient precipitation regime (Trt. 1): In six of the RaMPs, rainfall is collected and reapplied to the plots each time a natural rainfall event occurs. Rain gauges outside the RaMPs and an in-line flowmeter allows us to confirm that precipitation amounts applied inside the RaMPs equal the amounts of rain falling outside.

Altered precipitation regime (Trt. 2): The other six RaMPs are used to impose a predicted future rainfall regime of increased temporal variability in rainfall inputs (Fig. 2) and soil moisture (Fig. 3) relative to ambient precipitation patterns. This is achieved by lengthening the current ambient dry intervals between rainfall events by 50%. For example, a 2 week period between ambient rainfall events would be lengthened to 3 weeks. All rainfall during these experimentally lengthened dry periods is stored and applied as a single larger event at the end of the dry interval. The total amount of growing season rainfall applied in this treatment is identical to ambient, only the event size and temporal distribution of inputs is altered.

Increased air and soil temperatures with ambient or altered rainfall patterns (Trt. 3&4): Each RaMP contains four 2 x 2 m subplots. Overhead rectangular IR lamps (Kalglo MRM-1215 1500-W model) are suspended ca. 1.5 m above the canopy in two subplots. The lamps simulate climate warming (~2 ^{o}C) by enhancing downward IR flux (~75 W m^{-2}) to the soil surface/plant canopy and reducing the diurnal range in air temperature. In contrast to rainfall treatments, warming occurs year round. We raise the lamps during the growing season as vegetation height increases to maintain a constant IR flux at the canopy surface, and to avoid unrealistic radiation loads on the canopy. The 4-m^2 plots are of sufficient size to allow us to designate 1-m^2 areas (4/RaMP) for non-destructive plant species composition sampling, as well as areas for ANPP estimates (0.1 m^2 quadrats), and other response variables measured as outlined below. Initial performance of the IR lamps and effects on canopy temperatures and soil moisture indicate that the treatment is effective (Fig. 4).

This NIGEC project focused primarily on belowground responses to changes in rainfall patterns and ambient temperatures. However, to fully evaluate the impact of climate change on grassland ecosystems, these results must be integrated with comparable studies of aboveground processes, including plant ecophysiological responses, changes in aboveground productivity, and shifts in plant species composition. We have been addressing these aboveground responses with additional funding from the USDA and NSF. In Table 1, we summarize the main above- and belowground responses being measured.

Table 1. Summary of response variables, methods and investigator responsibility.		
Response	**Method**	**Responsibility**
Soil moisture	TDR/neutron probe	Research Assistant
Root growth and turnover	Minirhizotron	Fay/grad. Student
Root biomass and nutrients	Soil cores	Blair/Fay/student
Soil C and N	Soil cores/lab assays	Blair/student
N availability	Resin bags/soil extractions	Blair/Fay/student
Soil CO_2 efflux	Field chambers/LiCOR IRGA	Blair/student
Aboveground NPP	Harvest method	Fay/Knapp/LTER personnel
Plant species composition	Canopy coverage	Smith/Collins (non-NIGEC support)
Grass/forb gas exchange	LiCOR 6200 IRGA	Knapp/student
Plant water status	Pressure chamber	Knapp/student
Plant tissue C/N	Carlo-Erba C/N analyzer	Blair/LTER personnel
Microclimate	Micromet stations	Knapp/Research assistant

3. Research highlights

Our results indicate that changes in temporal and spatial variability in soil water content are key to explaining plant and soil responses to altered rainfall patterns, and we continued to document changes in soil water content throughout the funding period. We installed an automated TDR system to provide finer-scale temporal resolution for soil water measurements at 0-15 cm, while continuing to assess deeper soil water content with weekly neutron probe measurements. Altered rainfall timing (fewer, larger events and longer dry intervals) results in patterns of soil water availability markedly more variable than the typical present-day regime (Knapp et al. 2002). The soil surface layers remain dry for longer periods and deeper soil layers are recharged more often, causing reductions in both the mean and minimum levels of soil water in the upper soil (0-15 and 0-30 cm depths), despite both treatments receiving equal total rainfall quantities. The surface soil layer is critical since most grassland ecosystem-level processes and properties (e.g., ANPP, root depth distribution and N mineralization) are strongly linked to soil moisture at this depth. Across all years and treatments, we found that ANPP was positively correlated with mean soil water content at both 0-15 and 0-30 cm, and negatively correlated to variability in soil water content at these same depths (Fig. 5). That's important, as one of the effects of a more extreme rainfall regime in these grasslands is to decrease mean soil water content and increase variability in soil water content (Knapp et al. 2002). The altered rainfall timing treatment significantly reduced aboveground net primary productivity (ANPP) in most years, despite high year-to-year variability in ambient rainfall patterns and mean plant productivity (Fig. 6). Although the warming treatments have only been in place for 4 years, we have found that warming significantly reduced ANPP by ~12% in 2 out of four years to date (Fig. 7). To date, there have been no significant interactions between altered rainfall timing and warming on ANPP.

Earlier results from the RaMPs experiment indicated that altered rainfall timing decreased soil CO_2 flux, and that this decrease was related to increased variability in soil water content (Harper et al. 2005). Results during the current funding period supported these earlier findings (Fig. 7), and indicated that a simple change in the temporal distribution of rainfall, with no change in quantity, can significantly reduce both plant productivity and soil respiration. The responsiveness of both ANPP and soil CO_2 flux to changes in the timing, of growing season rainfall suggests that any increases in the temporal variability in soil water content resulting from climate change will significantly alter key C cycling processes in grassland ecosystems. Increased temperatures are predicted to reduce shallow soil moisture even further, and may amplify the effects of increased soil moisture variability. In the first four years of experimental warming, we found that warming reduced both plant productivity and soil CO_2 flux (Fig. 8), though not in all years. In the case of soil respiration, it appears that the effect of warming varies with mean growing season precipitation (Fig. 9). We attribute the negative impact of heating on soil CO_2 flux to increased water stress in the heated treatments, which suggests that the effects of warming may differ in more mesic ecosystems (i.e., forests and tundra) and those where water availability can limit soil processes (i.e., semi-arid grasslands). In contrast, the effects of warming on plant productivity were not predictable based on mean annual precipitation only, suggesting that other factors (e.g., timing of precipitation and water deficits) may be more important.

Changes in patterns of rainfall and soil moisture dynamics should also affect root biomass, production and turnover. In order to address these changes we took deep soil cores (~1.5 m) in 2000 to document patterns of root biomass and depth distribution, as well as root tissue C and N content. Results of this root harvest indicated significant shifts in plant root:shoot ratio, with higher root:shoot ratios in the altered rainfall timing treatment (Fay *et al.* 2003a). The destructive nature of these samples limits the frequency with which they can be made, but we will repeat this sampling following the 2007 growing season. We also are using a non-destructive minirhizotron approach to assess fine root dynamics with more frequent measurements. A preliminary assessment of minirhizotron data from the RaMPs suggests that fine root length density in the upper soil (0-30 cm) is declining with altered rainfall timing, consistent with observed changes in ANPP.

Climate change may also alter soil N mineralization, and we continued to assess potential changes in N availability in response to the rainfall timing and warming treatments. We predicted that altered rainfall patterns and increased temperatures will affect patterns and rates of N mineralization, with brief periods of high N availability limited to when dry soils are rewetted. Our results showed that increased rainfall variability in the RaMPs doubled resin-bag collected nitrate (Figure 10). In contrast, we have found no effects to date of warming on soil N availability. The increase in nitrate concentrations, coupled with reduced plant growth and larger precipitation inputs suggests the potential for increased N losses under a more extreme rainfall regime.

In addition to the project-specific activities indicated above, we also participated in a related project designed to assess plant physiological and genomic responses to the rainfall timing and warming treatments. This project, funded by the DOE PER program, complements our current

NICCR-supported research and will provide a more comprehensive evaluation of responses to climate change from the level of genes to whole ecosystems.

4. Research products

A web page (http://www.konza.ksu.edu/ramps/) was established to facilitate dissemination of information about the experimental approach being used (i.e., RaMP design and operation) and project results-to-date.

5. Publications (2006-2007 only)

Nippert, J.B., A. K. Knapp and J.M. Briggs. 2006. Intra-annual rainfall variability and grassland productivity: can the past predict the future? *Plant Ecology*, 184, 65-74, 2006.

Porporato, A., G. Vico, and P.A. Fay, Superstatistics of hydro-climatic fluctuations and interannual ecosystem productivity, *Geophys. Res. Lett.*, 33, L15402, doi:10.1029/2006GL026412, 2006.

Swemmer, A.M., A.K. Knapp and M.D. Smith, Growth responses of two dominant C_4 grass species to altered water availability, *International Journal of Plant Science, 167,* 1001-1010, 2006.

Travers, S.E., M.D. Smith, J. Bai, S.H. Hulbert, J.E. Leach, P.S. Schnable, A.K. Knapp, G.A. Milliken, P.A. Fay, A. Saleh and K.A. Garrett, Ecological genomics: making the leap from model systems in the lab to native populations in the field. *Frontiers in Ecology and the Environment. Frontiers in Ecology and the Environmen*t, 5**,** 19-24, 2007.

Figures:

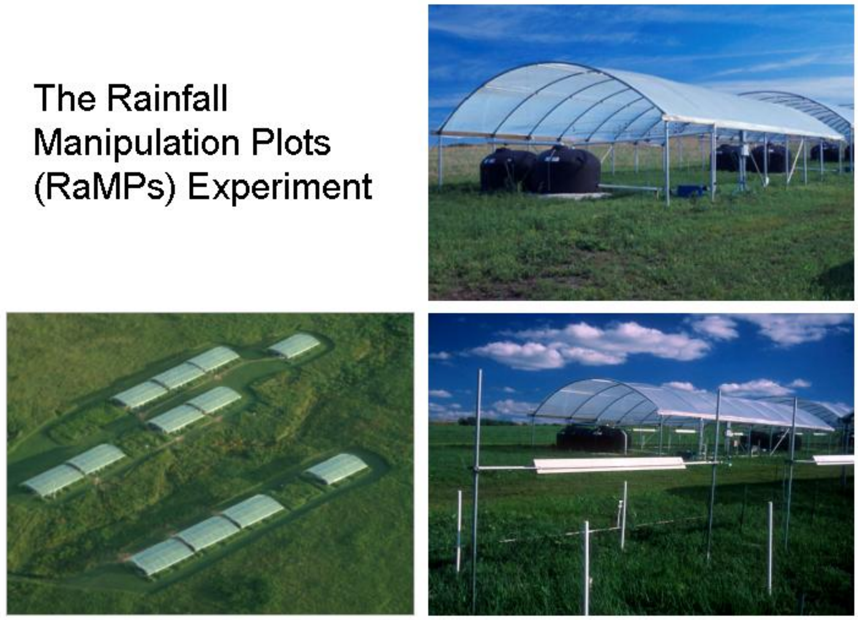


Fig 1. **Bottom left: Aerial view of the RaMPs experimental site. Top right: View of one Rainfall Manipulation Plot (RaMP) prior to installing IR lamps. Bottom: IR heating lamps in a reference plot in the foreground. See text for a more detailed description of shelter design and operation.**

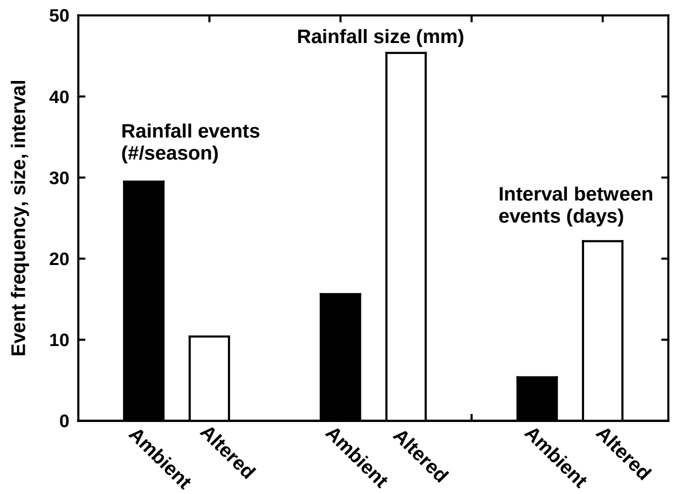


Fig 2. **Comparison of key characteristics of growing season precipitation the Ambient and Altered rainfall timing treatments, illustrating the changes in number of growing season rainfall events, mean rainfall event size, and mean length of dry interval between rain events in the RaMPs experiment.**

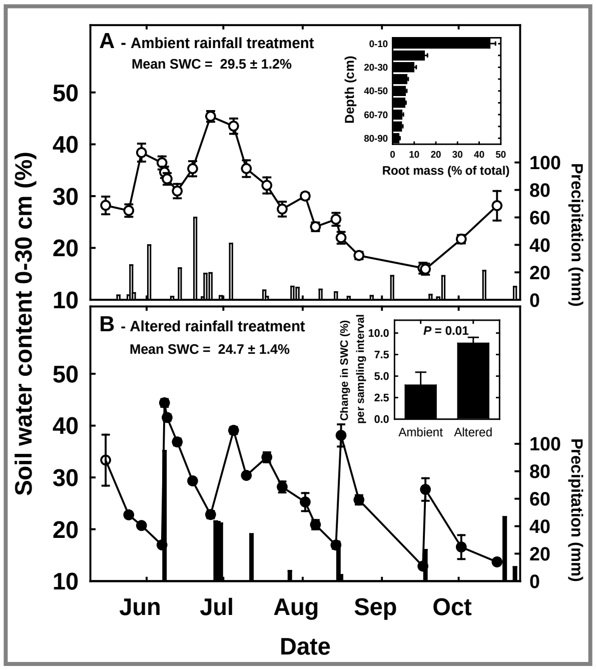


Fig. 3. Seasonal patterns of volumetric soil water content (SWC) integrated over the upper 30 cm of the soil in plots that received either precipitation inputs identical to ambient patterns during the growing season (top panel) or plots exposed to an altered rainfall regime (bottom panel) in which dry intervals between rain events were extended and individual storms were larger (compare precipitation patterns at the bottom of each panel). Total rainfall amounts were the same for each treatment. Mean root biomass distribution by depth for all treatments combined is shown in the upper inset (there was a trend towards deeper roots in the altered rainfall plots). The mean absolute difference in SWC between sampling points, a measure of temporal dynamics, is shown in the lower inset. From Knapp *et al*. 2002.

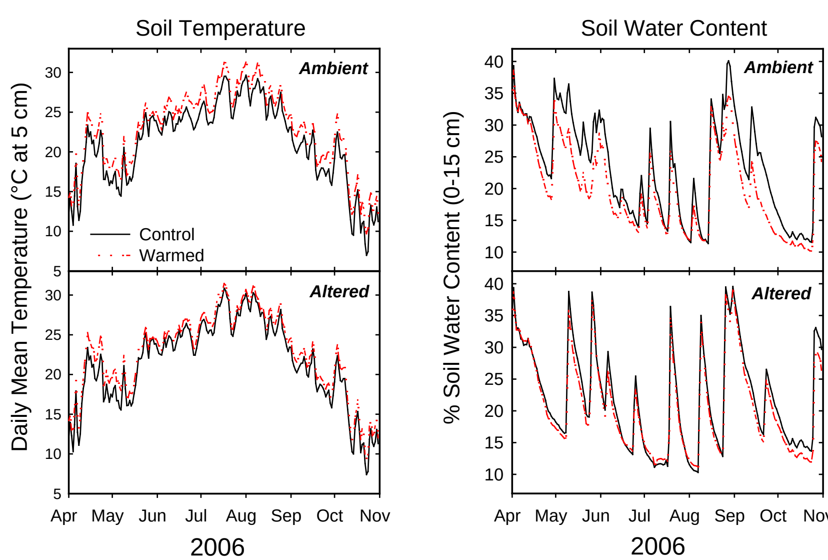


Fig. 4. Increase in the average canopy temperature and decrease in soil water content (0-15 cm depth) in RaMP subplots heated by IR lamps.

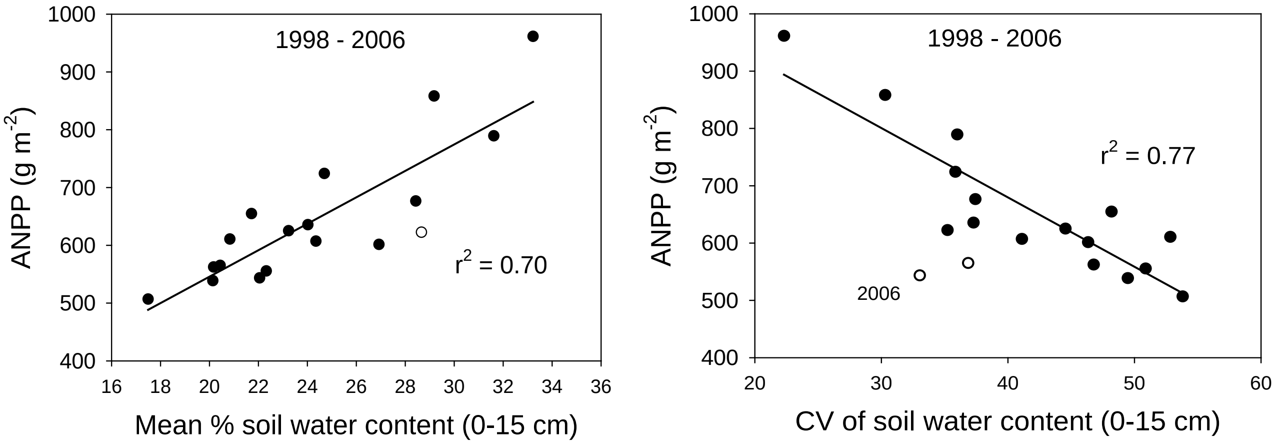


Fig. 5. Across all years and treatments, ANPP was positively related to mean seasonal soil water content in the upper soil (0-15 cm) and negatively related to variability in soil water content. Note: 2006 was an unusually dry summer, with both low mean soil water content and low variability in soil water content throughout much of the growing season.

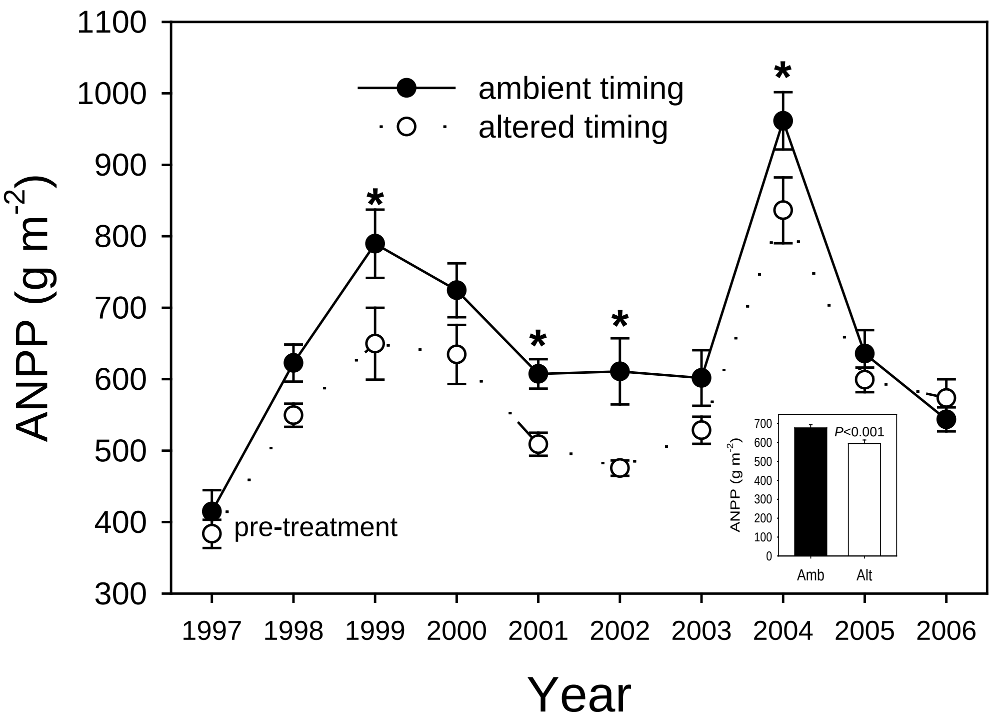


Fig. 6. Summary of plant productivity responses to the rainfall timing treatments from 1998-2006. Altered rainfall timing significantly reduced ANPP by 13-22% in 4 of 9 years, and had a significant main effect when analyzed across all years (inset).

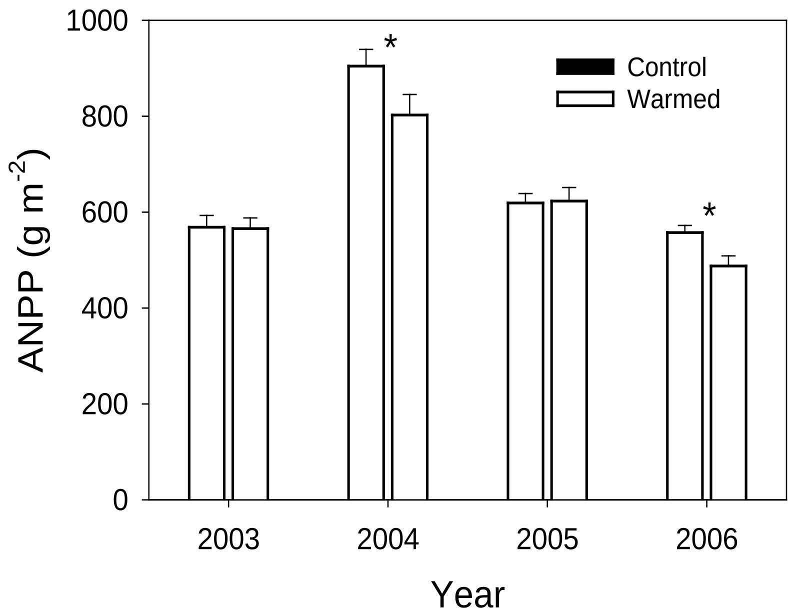


Fig. 7. The effect of warming on ANPP varied by year. In years when warming had a significant effect, it was to reduce ANPP by ~12%.

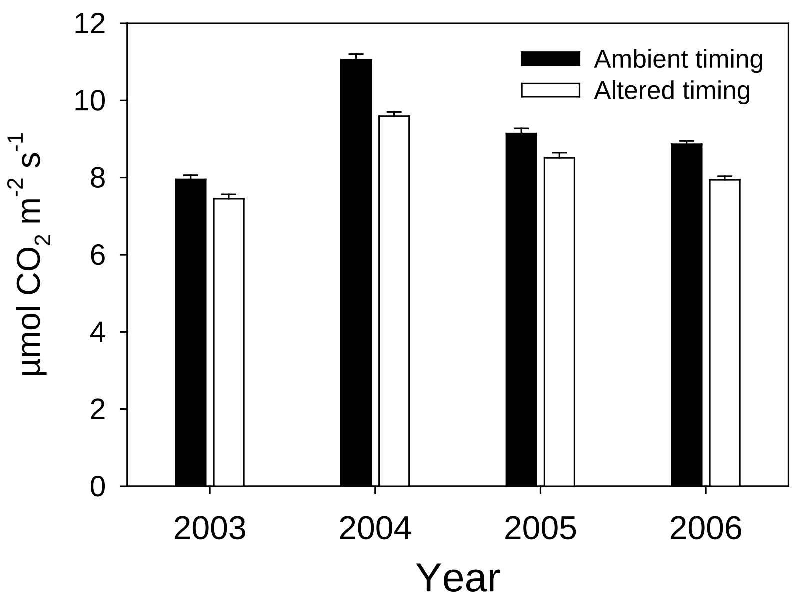


Fig. 8. Mean seasonal soil CO_2 flux was significantly reduced by ~10% across all years by a more extreme rainfall regime. These results are consistent with earlier results in Harper *et al.* 2005.

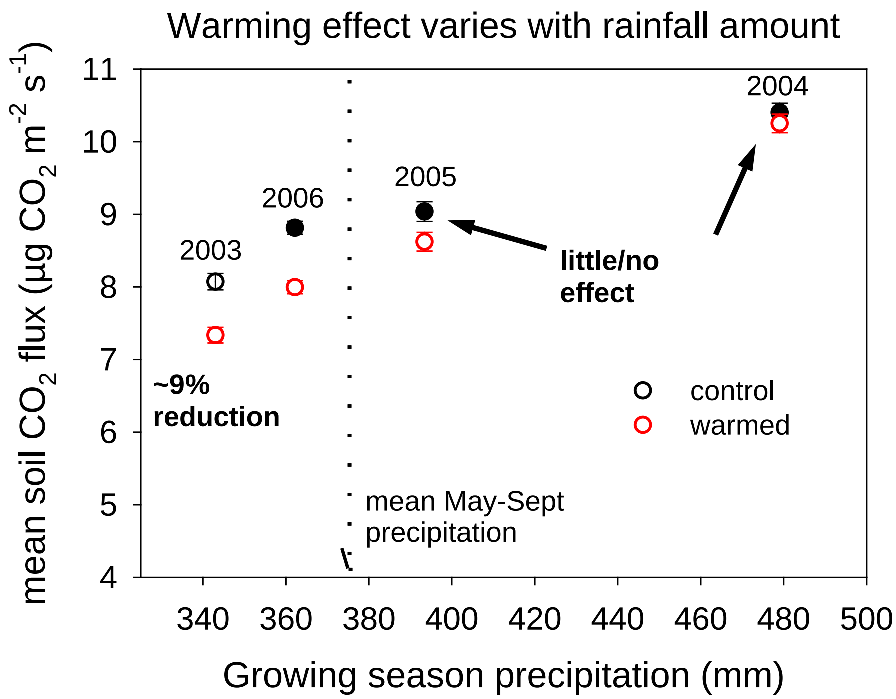

Warming effect varies with rainfall amount
mean soil CO_2 flux (µg CO_2 m^{-2} s^{-1})
11
10
9
8
7
6
5
4
2004
2005
2006
2003
little/no effect
~9% reduction
control
warmed
mean May-Sept precipitation
340
360
380
400
420
440
460
480
500
Growing season precipitation (mm)

Fig. 9. **The effect of warming on warming soil CO_2 flux varied as a function of growing season precipitation amount. There was little effect of heating in years with above average precipitation, but an approximate 9% decrease in soil CO2 flux in years with below average rainfall, suggesting that the effect of warming is mediated by soil water availability.**

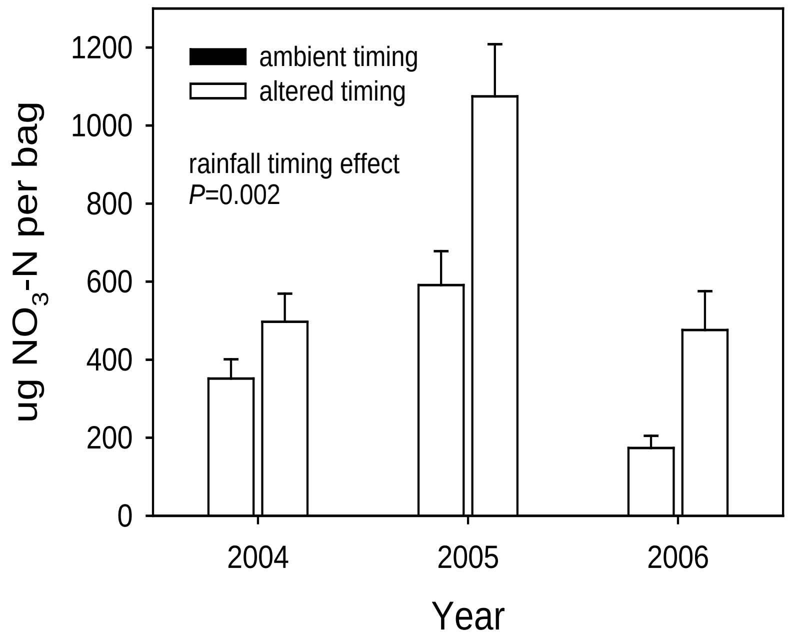


Fig. 10. Altered rainfall timing significantly increased nitrate recovered with buried resin bags (10 cm depth). There was no effect of rainfall timing on resin-collected ammonium, and no effect of heating on resin-collected nitrate or ammonium.

Are North Temperate Wetlands A Persistent Net Source of Atmospheric CO_2? Component and Whole-System CO_2 Fluxes in a Landscape Mosaic

Paul Bolstad, University of Minnesota, and Ken Davis, Pennsylvania State University

Abstract

Our overall objective in this research was to improve our knowledge of the magnitude, direction, and environmental drivers of CO_2 exchange in wetlands, and flux contributions of disturbed uplands**.** This research sought to quantify the relationships between CO_2 exchange and underlying environmental factors that vary on daily, seasonal, annual, and longer time scales, to identify the relative influence of species, terrain position, disturbance, and climate on carbon balance, and help quantify the carbon balance of terrestrial ecosystems in the United States.

This research is important because of potential positive feedbacks between climate change and carbon stored in forest and wetlands. Warmer and dryer climates are likely to result from the CO_2 humans have added to the atmosphere. Soils will warm, and longer growing seasons will cause more water use by plants, and therefore dryer soils. High water tables keep much carbon from decomposing. As wetlands dry, this carbon may be lost to the atmosphere, increasing warming, and causing more drying, in a positive feedback. In a similar way, increased temperature may increase mortality, slow establishment, or decrease growth on drier upland sites. However, drying of wetlands could also increase productivity on those sites, and longer growing seasons may increase forest growth on mesic upland sites, in part offsetting carbon loss from soils. This project measured carbon balances and productivities in various wetland and recently disturbed forest ecosystems.

Research Activities

The research was conducted in Price and adjacent counties in north central Wisconsin, at or near a set of eddy covariance flux towers. Primary study sites were located near the Lost Creek flux tower, an 8-meter eddy flux facility in an 800 hectare alder/sedge fen. A smaller set of flux measurements were collected below the WLEF Tall Tower, a regional flux measurement system. Supporting vegetation structure and productivity measurements were collected near the flux towers.

We tested the hypotheses that clearcuts and wetlands are primary sources of net ecosystem carbon flux to the atmosphere, and that variation in this flux is primarily driven by interannual variation in water balance and temperature. Our hypotheses were that longer, warmer, drier growing seasons will lead to an increase in net ecosystem to atmospheric C export, primarily due to decreased water tables and increased aerobic decomposition in wetlands, and increased temperatures and increased respiration in recently clearcut stands.

Eddy flux, chamber flux, biometric, and meteorological measurements were combined to estimate component and net carbon exchange in a number of vegetation types, landscape positions, and time periods. Biomass accumulation/surface flux method were compared to eddy flux measurements in a test of convergence. Data from both methods were combined with vegetation structure and meteorology to identify primary controls on flux variation and to develop and test plant environment models of carbon exchange. Our measurements and schedule did not deviate substantially from the proposal that funded this work.

Research Highlights

This project in part funded collection of flux data from the Lost Creek wetland tower (c, Figure at right), and component flux measurements in the footprint of the WLEF Tall Tower (a, at right). One of our main hypotheses is that disturbance, primarily clearcuts, cause the WLEF region to be a carbon source from ecosystems to the atmsophere, and wetland drying provides a second carbon source. The results of research addressing the first hypothesis are described towards the end of this document. This first part describes measurements and analysis of wetland fluxes and causes.

The Lost Creek shrub wetland is a small but stable sink for atmospheric carbon, despite a consistently declining water table. We reject our hypothesis that there is a net loss of carbon from these sites, based on the eddy flux, chamber flux, and biometric measurements. While decreased water tables have resulted in a significant increase in net ecosystem respiration over the study period, this has been offset by a concomitant increase in net production, resulting in little change in net ecosystem carbon balance. The Lost Creek watershed is remarkable mostly for the lack of variation in the annual net or yearly time course of net carbon flux, despite larger interannual variation in climate.

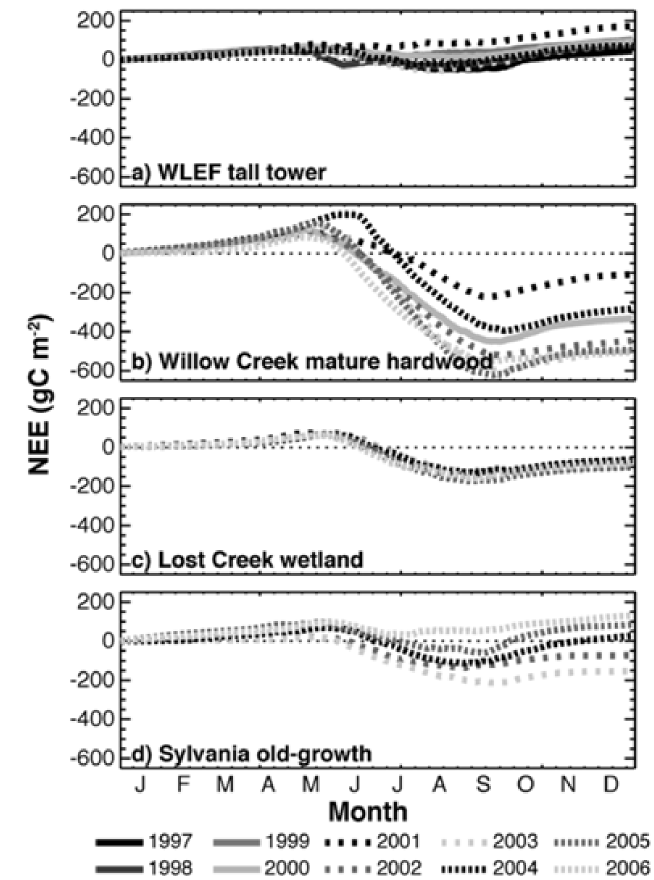
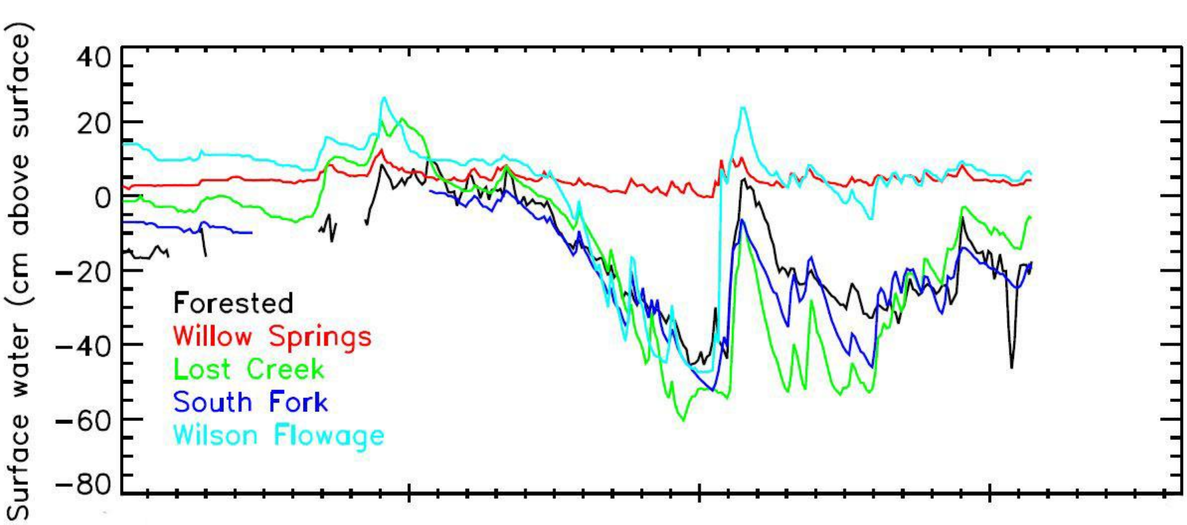


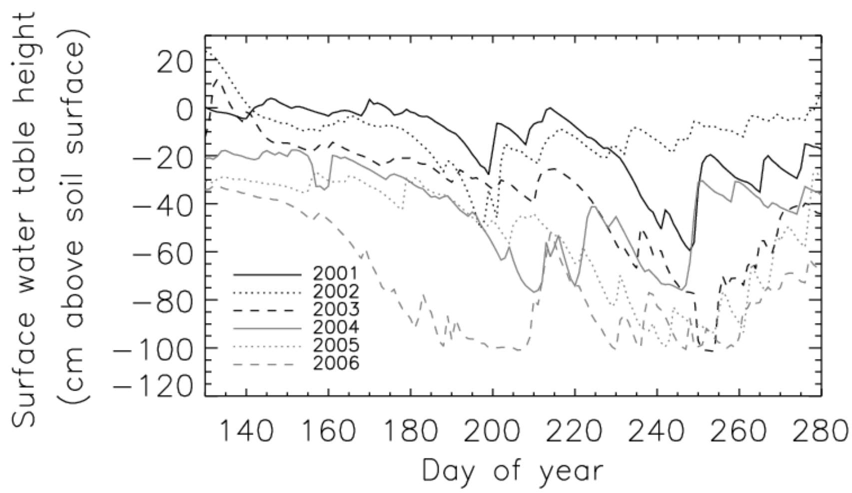
Figure 2: Annual cumulative flux at four flux towers, including WLEF (landscape mosaic), Willow Creek (2nd growth deciduous), Sylvania (old-growth deciduous), and Lost Creek (shrub fen wetland).

We observe widespread, coherent declines in water levels driven primarily by annual water balance in a number of wetlands, although this response was not uniform, and varied by site. We operated a network of water depth sensors. These pressure transducers were calibrated and placed at approximately one-meter depths in a set of wetlands. Piezometers in upland, isolated wetlands were most sensitive to near-period environmental conditions (Lost Creek, South Fork, in Figure below), while at regional springs (Wilson Springs), or where water levels were subject to control by downstream dams (Wilson Flowage) showed less coherence or more variable water depths.

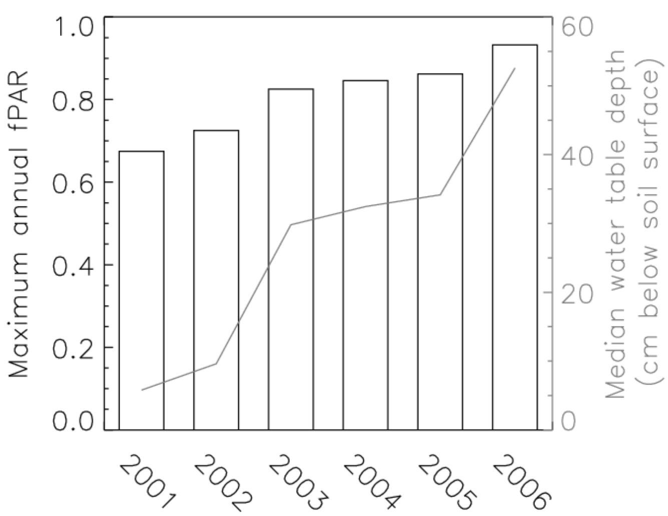


These results are important, because they establish regional coherence in water table response, but varying depending on hydrologic position in the landscape, and water management. Carbon protection by inundation has been noted in the literature as a major “protection” mechanism, and this mechanism may be altered by changing climates (for example, see Davidson and Jansens, Science, 2006, 440:165-173). There is the real prospect to measure and model this change in soil hydric status and hence protected carbon dynamics. However, hydrogeology and management must be considered.

At the Lost Creek flux tower site, there were both annual trends in Spring to early Fall water drawdowns, as plant water demand outpaced precipitation inputs. Other measurement sites show regional downward trends spanning the study period (Figure at right). Water table drawdown commenced within a few week lag of leaf out, which is noticeably advanced with early Spring temperatures. This establishes a link between water levels and temperature, as the extent of the growing season substantially affects total water use.



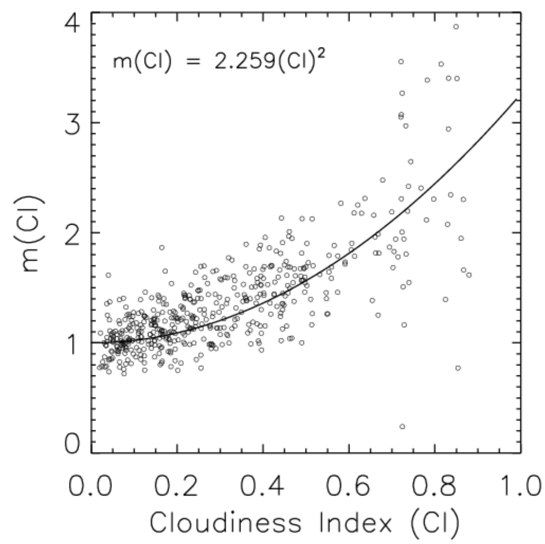
We noted a strong relationship between water table height and annual production. This production is related to an increase in total leaf area, measured both biometrically and via absorbed photosynthetically active radiation (fPAR). The graph below shows the increase in depth to the water table at the Lost Creek shrub wetland with a concomitant increase in fPAR.

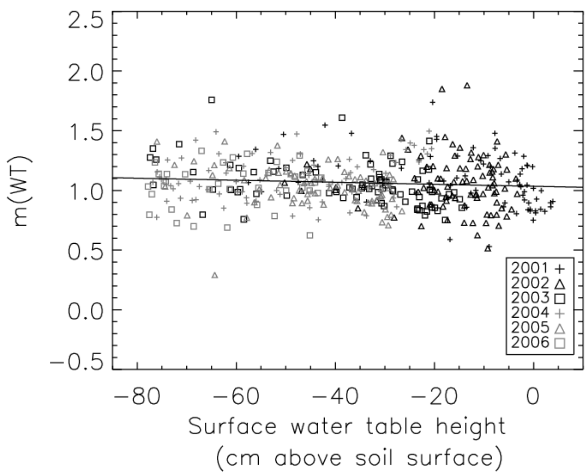


These observations were used to test our hypothesis of link between water table and carbon balance, via a model-based approach. Particularly, we tested whether water-table effects would significantly improve the functioning of a light use efficiency model, driven by the standard factors of PAR, fPAR, minimum daily temperature (Tmin) and vapor pressure deficit (VPD):

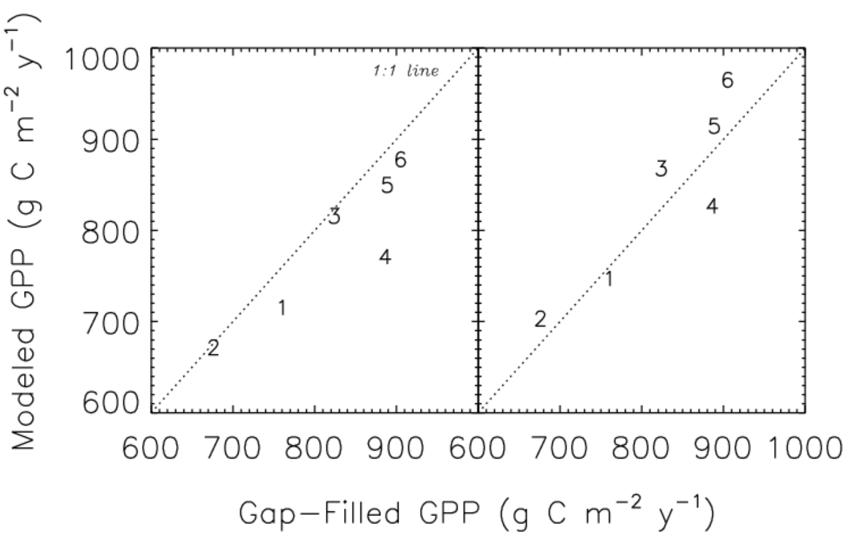
$$GPP = \downarrow PAR \times fPAR \times \varepsilon_{max} \times m(T_{min}) \times m(VPD)$$

We modified this relationship to include both a cloudiness index, m(CI), and a water table index, m(WT). Both of these factors proved statistically significant in fitting the GPP model to the Lost Creek tower flux and micrometeorological measurements:





GPP models that included these two factors were substantially better at predicting observed values than reduce model forms. Below, the plot on the left shows the model fit with the cloudiness factor m(CI), while the plot on the right shows the improvement when including water table effects:



Modeled net ecosystem exchange (NEE) was significantly different with the addition of the cloudiness index and the water table index. While there was a relatively small (ca. 10%) change in estimated GPP, there was a large (ca. 55%) change in the model-estimated NEE, a substantial improvement in the model with these two factors. Our results suggest we turn our attention to implementing these two factors in northern biomes, where wetlands are an important, often dominant portion of the landscape.

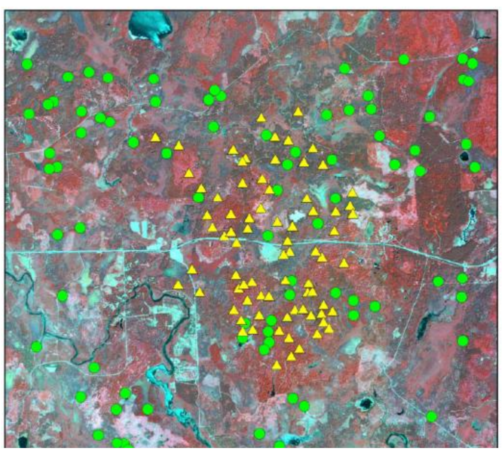
Our work above noted significant changes in productivity as important wetland responses to directional changes in water table. This justified the development of LiDAR-based methods to estimate ecosystem biomass and productivity across a wetland/upland mix, with 2006 measurements in wetlands directly funded by this current project (below, top left). Much work has shown the potential for LiDAR to substantially improve estimates of forest structure and biomass gain. However, this research has focused primarily on conifers in plantations, and on stemwood biomass. This is the first application to deciduous hardwoods, forest wetlands, and forest shrublands to our knowledge, and the first test for production in these or related types.

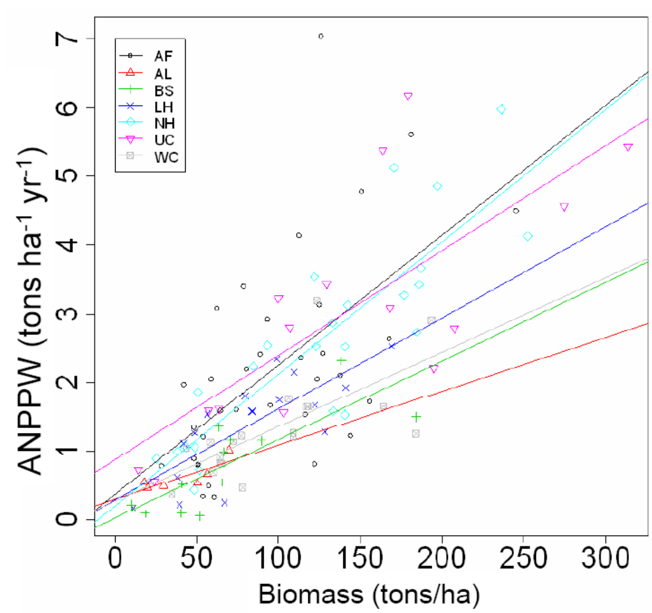
We found significant relationships between LiDAR density and height metrics and biomass (not shown), and then relationships between LiDAR metrics, biomass, and aboveground woody production (below, top right). A significant finding is that these relationships are species-specific. These led to strong predictive relationships on a per-plot basis (figure, bottom left), relationships that are even stronger when applied on a per-stand basis.

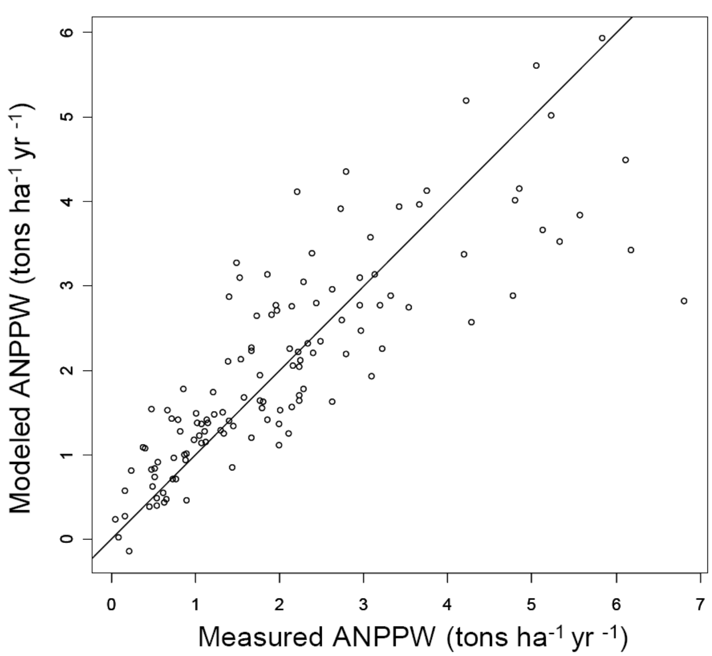
Aboveground production varies across a broad range. Woody production is generally lower than potential values in uplands because of less than complete stocking. Wetland above ground production is quite low compared to upland production.

Once fit, these LiDAR metrics may be applied to the near continuous measurement field the LiDAR provides (Figures, next page). Spatially exhaustive estimates may be produced for biomass and productivity with known precision on areas corresponding to plot sizes, in this case, approximately 200 square meters. When aggregated to larger sizes, e.g., hectares to stands of several hectares, there is a corresponding decline in the coefficient of variation.

LiDAR methods have the potential to reduce our uncertainties in stand carbon accrual by an order of magnitude.

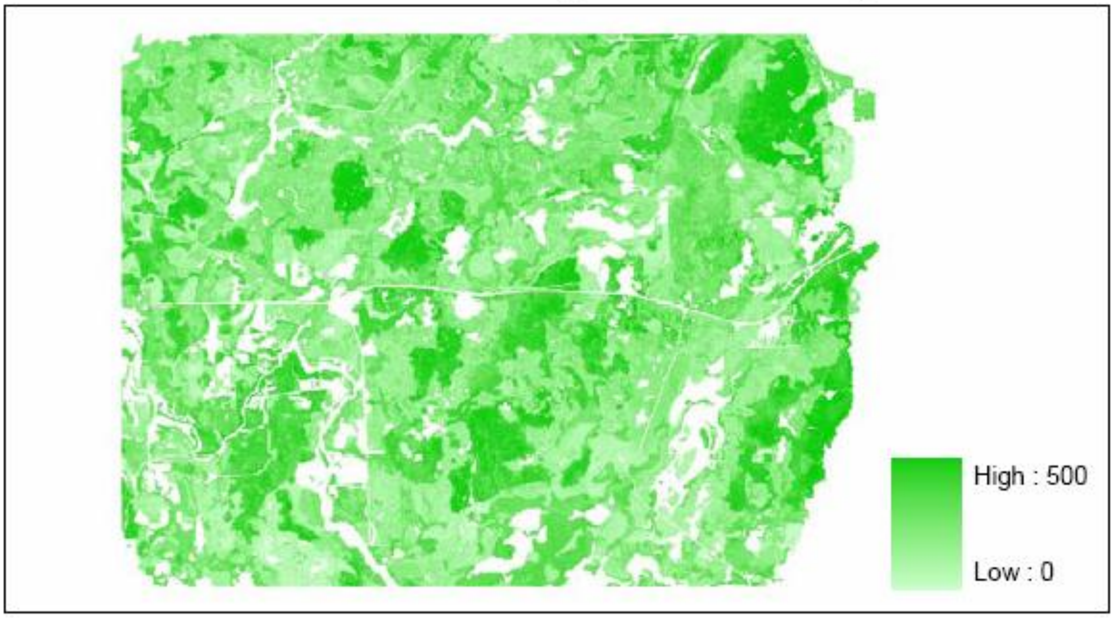




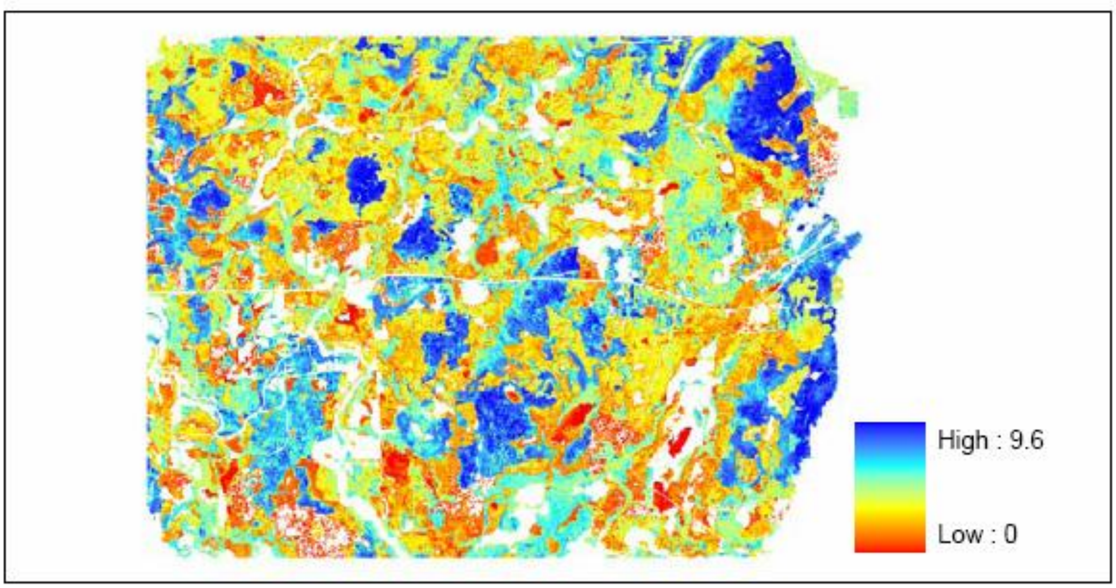


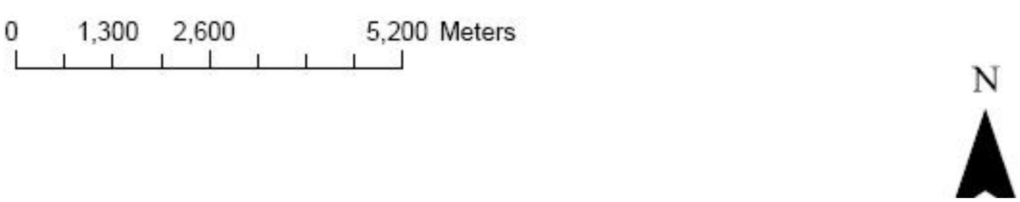
Key:
AF = Aspen/Fir
AL = Alder
BS = Black Spruce
LC = lowland conifer (N. White Cedar)
LH = Lowland hardwoods
MX = mixed hardwoods/conifers
NF = nonforest
UC = Upland conifers
UH = Upland hardwoods

Biomass (tons ha^{-1})



ANPPW (tons $ha^{-1}yr^{-1}$)





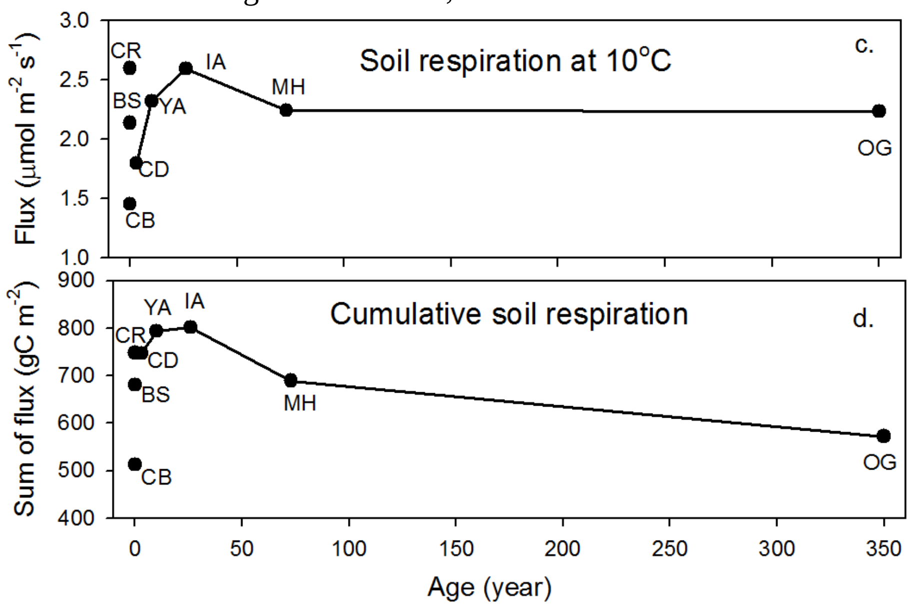
Soil respiration was the other dominant flux that defines carbon balance. We noted strong, age-related patterns to soil respiration in deciduous forests. These patterns showed respiration that was highly variable but generally similar in clearcuts to mature forests, with a rise in soil respiration after harvest, through maximum rates in intermediate-aged deciduous forests, followed by a decline levels observed in mature forests. These moderate rates were also observed for an old-growth forest.

The figures below highlight these trajectories. The plots BS (blowdown-shrub/aspen), CB (clearcut-burn), CD (clearcut-dense regeneration), and CR (clearcut-wet site) are all recently (<3 year) disturbed sites, with aspen regeneration. YA are young aspen sites (5-10 years), IA are intermediate aged aspen (12-20 years), MH are mixed aspen hardwood sites (40-80 years), and OG is an oldgrowth site (350 years). This figure demonstrates the trajectory of respiration, both at a fixed temperature, and at observed field temperatures, over this chronosequence. Other factors were controlled as much as possible within the limitations of a substitution of space for time, in that the geographic location, topographic position, and soil characteristics were matched as much as practically possible.

The pattern of increasing respiration rates at a standard temperature are clear in the top graph, below. These data show average growing season flux, measured with both continuous recorders and spot measurements, then used to fit a site-specific exponential model (n> 30, r2>0.8 for all models), and finally respiration predicted at 10 degrees C. The variation in rates due to disturbance history is evident in the clearcut sites, but the mean value is near CD, which is also the site most representative of clearcuts in the region. Respiration increases with age until intermediate aspen (IA), and then declines through mature hardwoods to similar values in old growth.

Note that his pattern is largely represented when cumulative annual soil respiration is estimated (bottom panel, figure below). Respiration at younger ages is elevated, because soil temperature and hence realized respiration are higher at clearcut sites. There is less shading, more solar insolation reaching the soil, and hence higher temperatures. However, we also note that the peak respiration rates at high temperatures are lower than they would be at equivalent high temperatures for the older forest sites. However, these rates were not reached at the higher forest sites, so the cumulative flux was elevated at disturbed sites.

This leads us to conclude, however, that care must be taken when applying regional soil respiration equations, as is commonly done. This would lead to a gross overestimation of flux from clearcut or other sites that regularly reach high soil temperatures, if site or type specific soil respiration equations aren't developed and applied.



Research Products
Our data are maintained and distributed via the ChEAS website, at the Pennsylvania State University, Department of Meteorology. These include the processed and gap-filled flux data, site micrometeorology, and site characterization and biometric measurements. The website is http://cheas.psu.edu

These data have also been submitted to Ameriflux and NASA maintained data archives.

Publications
Wang, W., K.J. Davis, B.D. Cook, D.M. Ricciuto, and M.P. Butler, 2006. Decomposing CO2 fluxes measured over a mixed ecosystem at a tall tower and extending to a region: A case study, *Journal of Geophysical Research - Biogeosciences*, **111**

Accepted
Desai, A.R., A. Noormets, P.V. Bolstad, J. Chen, B.D. Cook, K.J. Davis, E.S. Euskirchen, C.M. Gough, J.M. Martin, D.M. Ricciuto, H.P. Schmid, J. Tang, and W. Wang, submitted. Influence of vegetation and climate on carbon dioxide fluxes across the Upper Midwest, USA: Implications for regional scaling, *Agricultural and Forest Meteorology*.

Noormets, A.N., D.M. Ricciuto, A.R. Desai, B.D. Cook, J. Chen, K.J. Davis, P.V. Bolstad, E. Euskirchen, P.S. Curtis, and H.P. Schmid, submitted. Moisture sensitivity of ecosystem respiration: Comparison of 14 forests in the Upper Great Lakes Region, USA, *Agricultural and Forest Meteorology*

Submitted
Cook, B.D., P.V. Bolstad, F.A. Heinsch, K.J. Davis, W. Wang, R. M. Teclaw, and D.D. Baumann, Surface water table as a constraing on MODIS GPP estimates in a shrub wetland. Submitted, Journal of Geophysical Research.

In Preparation
Tang, J., P. V. Bolstad, J. G. Martin, 2007. Soil respiration in a Great Lakes forest chronosequence, submitted, Journal of Geophysical Research.

J. Tang, P. V.Bolstad, K. Davis, A. Desai, N. Saliendre, P. Weishampel, Age effects on carbon and water fluxes in the Great Lake forests.

Tang, J., P. V. Bolstad, Aboveground carbon stock, net primary productivity, and plant respiration in a Wisconsin wetland.

Maxa, M., and P.V. Bolstad. Wetland mapping with LiDAR and high resolution satellite data.

Student Degrees Supported
Ryan Anderson, M.Sc., completed October, 2007.
Bruce Cook, Ph.D., expected completion June, 2008.
Ryan Kirk, Ph.D., expected completion June 2008.

CIMAP Final Report

I. Title: Climate Impact Modeling and Analysis Project (CIMAP)

II. Abstract

Model selection and input data errors are two important sources of uncertainty in climate impact studies. The overall objectives of this project were to determine the reliability of two of the most commonly used crop models, EPIC and CERES, in simulation of grain sorghum yields in the southern and central Great Plains and to investigate uncertainties that are potentially introduced by different input data sources. Historical field-trail data from Mead Experimental Center, NE and NASS county-level yields from 46 selected stations across the region were used for analysis. With respect to the Mead experimental data, CERES model systematically under-predicted yields by about 30%, while EPIC simulated virtually “un-biased” and reasonably accurate results. Comparison of model elements suggests that CERES’s poor-performance was mostly due to over-prediction of water-stress days and failure to simulate N-stress. Uncertainty analysis of the EPIC model showed that alternative input data, if carefully selected, only had limited impacts on model output uncertainty. With regard to simulating historical NASS sorghum yields, EPIC was found to be about 10% more reliable than CERES under all range of climate conditions (normal or extreme). However both models demonstrated great spatial variability in reliability throughout the region. We therefore concluded that EPIC was generally superior over CERES in simulation of historical sorghum yields in central Great Plains. However, differences between two models were location-depended. Future studies are desirable to explore the temporal/spatial patterns of model reliabilities and to develop strategies to integrate/synthesis multi-model results to reduce the uncertainties in climate impact assessment.

III. Research activities

Due to changes in funding policy that eliminated the participation of the National Center for Atmospheric Research (NCAR) in Year 3 of the CIMAP project, the revised major objectives were to evaluate:

1. How accurately do EPIC & CERES crop models simulate historical sorghum yields (NASS, experimental) in the southern and central Great Plains? a) For the full range of climate conditions experienced over the historic record, and b) For subsets of years representing extremes in temperature and/or precipitation.

2. How accurately do component parts of process crop models reflect experimental data that were observed independently of data used to construct model algorithms? Whether two models agree or disagree each other on simulation of model components?

In addition, we made extra efforts to address the following questions:

3. What is the spatial distribution of model accuracy/reliability across the region?

4. What are uncertainties potentially introduced by different input data sources that are not site-specific but commonly readily available in climate impact studies?

Major research activities to address problems described above:

1. Geographic locations - A total of 46 stations were selected across the Great Plains to represent major sorghum growing areas in the region;
2. Data collections – We acquired/created the following data sets from different sources for model inputs and for output comparisons:
   a. Soil data – Sources include field survey data, STATSGO, SSURGO, and the USDA Nation Resource Inventory databases;
   b. Climate data – Historical records (1960-1995) for each of 46 stations were derived from NOAA database by the NCAR investigators;
   c. Crop management data – Field trail data (1973-2004) were acquired from Mead Experimental Center of University of Nebraska; Data for 46 stations were derived from a UADA-NASS agricultural handbook and other literatures and through personal communication with experts;
   d. Yield data – Include observations (1973 – 2004) from a field trail at Mead Experimental Center and NASS county-level yields of 46 stations (1960-1995).
3. Model preparations – To ensure a fair comparison, EPIC and CERES model were prepared and executed independently by investigators at PSU and NCAR, respectively, to best use their expertise and experience on the respective models. However, input files for both models were constructed from the same data sets described in activity 2;
4. Climate classification – Historical climate data (1960-1995) were classified into “normal T & P” and “extreme T or P” (i.e. warm/cold, wet/dry) crop-climate years. This approach was taken to evaluate the model performance under different climate scenarios and to fulfill the task described in object 1;
5. EPIC-Interface development - In an effort to facilitate EPIC model applications, we developed an EPIC-Interface program (see the Product section), which enables easy model preparation /execution for multi-runs and efficient management of model input/output data;
6. Error and uncertainty analysis – Using the Mead experimental data, we analyzed errors and reliabilities of the EPIC model under different climate categories. We also investigated uncertainties introduced by using different sources of input data;
7. Comparison of model reliability and model elements – Using statistical tools, we developed and applied a protocol to study model reliability and to compare overall model performance as well as individual elements (such as N-stress, water-stress, LAI, etc.) under normal or extreme climate conditions;
8. Mapping spatial variability – Results of model reliabilities were interpolated and mapped in a GIS to explore the spatial patterns of model performance;
9. Website development – a temporary website was developed to facilitate communications and data-sharing among research groups in NCAR, PSU, and University of Nebraska.

IV. Research highlights

1. Errors and reliability of EPIC model

Overall, the EPIC model was able to simulate sorghum yields with an acceptable accuracy (absolute relative error, *absRE* = 29%). The overall model reliability was about 56% (Table 1, Appendix). The degree of accuracy/reliability varied with climate-classes. However, there were no evidences that extremes in temperature and/or precipitation would worsen the model performance in general, when compared with that under normal situation. This is important because extreme conditions would become more critical in most projected climate change scenarios. The largest bias was under drought years (*RE* = -25%) and the most unreliable results were found in 0-N treatment (Reliability = 32%). More details can be found in Niu et al. (2008).

2. Uncertainties of the EPIC model

We investigated uncertainties by comparing model absolute relative error (*absRE*) between using base (site-specific) input data and using alternative input values (Table 2). Four alternative weather data included PARTIAL local data, a neighboring AWND, a distant COOP station, and model simulations (WxMDL). Soil data from two generalized soil databases, STATSGO and SSURGO, were used against field survey data. A heat-unit-index (HUI) based tillage schedule was compared with trial observations. In general, there was more than 70% probability that input-data-induced uncertainties were limited to less than 20% of *absRE*. When compared with model errors, the results suggest that internal structural uncertainties—that is uncertainties that derive of incomplete variable-process relations—in the EPIC model had a relatively larger impact on accuracy than uncertainties introduced by input data sources. However, one should be cautious when weather data from a distant station (e.g. COOP) or from complete model simulations are needed. More details can be found in Niu et al. (2008).

Table 2. Probabilities of differences in model absolute relative error between using baseline and alternative input values

Absolute Relative Error		<10%	<20%	<30%
WEATHER				
	PARTIAL	91	99	99
	AWND	48	69	88
	COOP	24	39	48
	WxMDL	20	39	60
SOILS				
	STATSGO	60	79	88
	SSURGO	47	74	87
MANAGEMENT				
	HUI	52	77	90

3. Model inter-comparison of errors

The distributions of EPIC and CERES model *absREs* were shown in Figure 1. An "L" shape by EPIC model and a "J" shape by CERES model indicate that the CERES model tended to produce more large/extreme errors. In addition, results also suggest that the CERES model systemically under-estimated sorghum yields by 30%, while EPIC model produced almost un-biased predictions (*RE* = -1.3%, data not shown). More details can be found in Easterling et al. (2008).

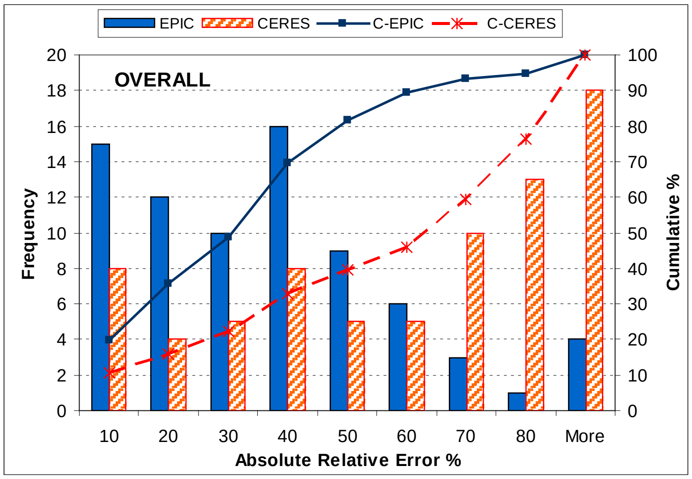


Figure 1: Frequency distributions of EPIC and CERES model absolute relative errors in simulation of experimental sorghum yields at Mead, NE

4. Reliability under different climate scenarios

Reliability was defined as the probability that a model will predict yield to within a desired accuracy (here <30% *absRE*). When compared with the historical NASS county level yield data from 46 stations across the region, we found that, overall, EPIC model was about 10% more reliable than CERRES model (Table 3). Similar trends were found under both normal T & P and extreme T or P scenarios. (Easterling et al., 2008)

Table 3: Comparison of reliabilities and extreme errors between EPIC and CERES models in simulation of NASS county-level sorghum yields

	YEARS	RELIABILITY %		EXTREMES %	
		EPIC	CERES	EPIC	CERES
OVERALL	1582	47	37	21	26
NORM T & P	806	46	37	22	25
EXTM T or P	776	48	37	15	27
T NORM	1151	45	36	23	26
T EXTM	431	52	39	14	27
T WARM	190	49	35	13	29
T LOW	241	55	43	15	25
P NORM	1103	48	39	20	24
P EXTM	479	45	32	22	30
P WET	237	49	36	27	20
P DRY	242	42	28	17	39

5. Comparison of model components

Selected model components, such as stress days (nitrogen, water, and temperature), water use efficiency (WUEF), harvest index (HI), and the maximum leaf area index (LAImax), associated with the EPIC and CERES comparison runs are presented in Table 4 (Appendix). In general, the EPIC model had more N stress days than CERES, especially for 0-Nitrogen treatment. However, CERES had more water stress days than EPIC. EPIC also used water more efficiently then CERES. The failure to simulate N stress under 0-N treatment and consistent severe water stress (> 76 days) under all climate scenarios (including P-WET) may explain, at least in part, the overall poor-performance of CERES model in this study. More details can be found in Easterling et al. (2008).

6. Spatial distributions of reliability

Both models showed great spatial variability in reliability across the region (Figure 2). Although EPIC model was relatively superior over CERES for majority areas, the CERES did show better results in the central NE and KS. This leads us to question the potential biases in model evaluations from a single station. More details can be found in Easterling et al. (2008).

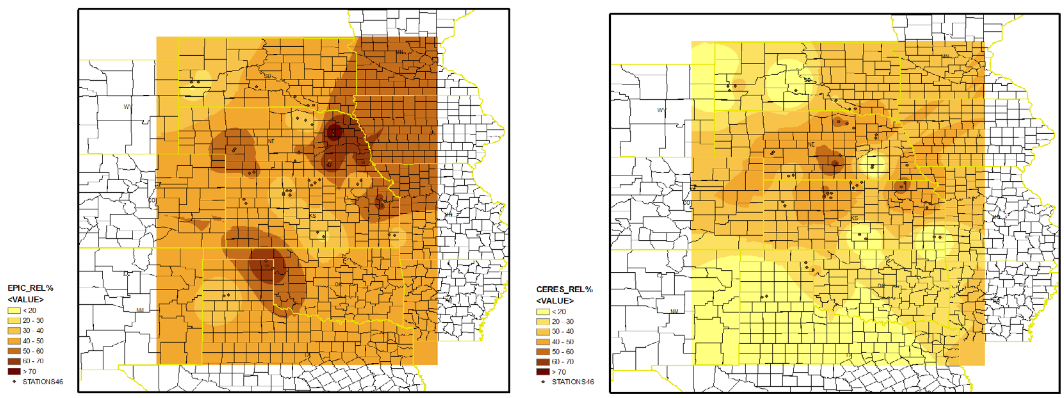


Figure 2: Spatial distributions of reliabilities of EPIC (left) and CERES (right) model in simulation of NASS county level sorghum yields.

7. Identification of needs for future studies

Previous studies suggest that different models often predicted different, even contradictory results of climate change impact on crop yields. For example, Mearns et. al (1999) found that CERES simulated a decrease of corn yields in the central Great Plains for one climate change scenario, while EPIC simulated no changes. Toure et al. (1994) even reported opposite signs of impacts from CERES and EPIC simulations. These uncertainties would certainly cause confusions in decision-making. The findings of this study suggest that model performances are climate- and location-depended. To reduce the uncertainties in climate impact assessment, we found the following issues that are desirable for further investigation: 1) identify/quantify (statistically) the temporal-(climate)/spatial patterns of model reliabilities; 2) develop strategies to integrate/ synthesis multi-model results by taking the temporal/spatial variability into account.

V. Products

An EPIC-interface was developed that enables a program automatically read input variable values from a specifically designed database file, generate formatted input files, execute multi-

EPIC-runs, extract selected variable values from original output file (text file) and save them back into the database for future analysis. The main purpose of this program was to facilitate EPIC model applications and efficient data management.

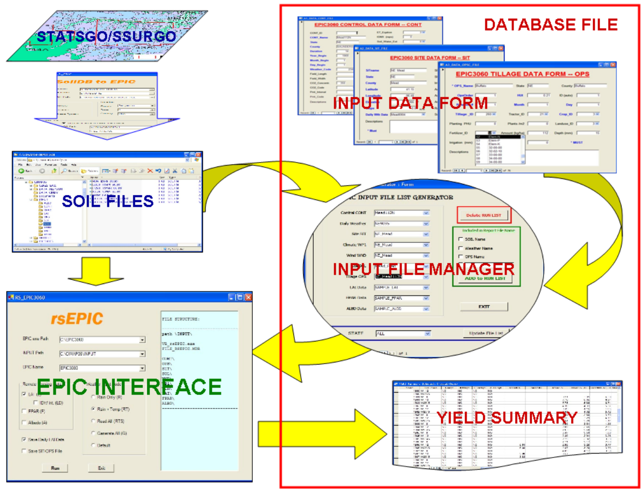


Figure 3: Diagram of the EPIC-Interface program

VI. Publications:

Niu, X., W.E. Easterling, C.J. Hays, A. Jacobs, and L. Mearns. 2008. Reliability and uncertainties of the EPIC model to estimate climate change impact on sorghum yields in the U.S. Great Plains. Agriculture Ecosystem & Environment:(under revision).

Easterling, W.E., X. Niu, C.J. Hays, L. Mearns, and L. Mcdaniel. 2008. Temporal and Spatial Comparison of EPIC and CERES Crop Models in Climate Impact Studies. Agricultural and Forest Meteorology:(in preparation).

VII. Graduate Students

Allyson Jocabs. 2007. MS in Geography. (??)

Appendix Table 1: Summary of EPIC model error and reliability analysis of sorghum yield simulations in Mead, NE

	YEARS	YIELD (T/ha)		Standard Deviation		RE %	absRE%	RMSE	nRMSE	PROBABILITY [1]	
		EPIC	OBSV	EPIC	OBSV					< 30%	> 50%
OVERALL	54	5.128	5.616	1.25	1.50	-0.44	29.23	1.80	32.09	0.56	0.13
NORM T & P [2]	26	5.064	5.565	1.23	1.65	3.59	37.67	2.02	36.28	0.42	0.19
EXTM T or P [3]	28	5.188	5.664	1.29	1.37	-4.18	21.39	1.57	27.81	0.68	0.07
T NORM	34	5.060	5.758	1.28	1.62	-1.78	33.41	2.00	34.66	0.50	0.18
T EXTM	20	5.245	5.376	1.23	1.27	1.84	22.13	1.41	26.32	0.65	0.05
T WARM	11	5.343	5.813	1.46	0.97	-6.44	20.58	1.57	26.92	0.64	0.00
T COLD	9	5.125	4.842	0.94	1.45	11.97	24.02	1.21	24.91	0.67	0.11
P NORM	41	5.199	5.658	1.25	1.43	0.76	31.95	1.86	32.87	0.51	0.15
P EXTM	13	4.907	5.483	1.28	1.76	-4.22	20.66	1.61	29.34	0.69	0.08
P WET	8	5.432	5.295	1.28	1.97	8.89	17.81	0.93	17.47	0.75	0.00
P DRY	5	4.066	5.783	0.79	1.51	-25.21	25.21	2.32	40.03	0.60	0.20
N 90 [4]	22	4.941	5.438	1.19	1.62	3.92	36.24	1.83	33.58	0.45	0.18
N 112	10	5.539	5.369	1.39	1.31	7.28	20.76	1.51	28.05	0.60	0.20
N 180	22	5.129	5.907	1.26	1.48	-8.31	26.07	1.90	32.16	0.64	0.05
N 0	22	2.287	3.100	0.66	1.28	-2.81	52.56	1.65	53.36	0.32	0.32

[1] Probability of *absRE* < 30% (i.e. reliability) or *absRE* > 50% (i.e. extreme errors).
[2],[3] T – temperature; P – precipitation; NORM – normal; EXTM – Extreme.
[4] N – Nitrogen fertilizer rate (lb/ac).

Appendix Table 4: Comparison of selected model elements between EPIC and CERES in simulation of sorghum yields at Mead Experimental Center, NE.

	YEARS	N Stress		Water Stress		Temp Stress		WUEF		HI		LAI max	
		CERES	EPIC	CERES	EPIC	CERES *	EPIC	CERES	EPIC	CERES	EPIC	CERES	EPIC
OVERALL	76	2	14	86	18	0	46	5.45	10.39	0.34	0.32	2.53	4.98
NORM T & P	37	2	15	87	14	0	50	4.74	10.32	0.34	0.31	2.33	4.99
ABNM T or P	39	2	13	84	21	0	43	6.13	10.47	0.34	0.32	2.72	4.98
T NORM	48	2	14	86	16	0	48	4.82	10.26	0.33	0.32	2.34	4.99
T ABNM	28	3	13	86	20	0	43	6.54	10.62	0.36	0.31	2.86	4.98
T WARM	16	1	14	93	23	0	31	5.77	10.90	0.35	0.33	2.30	4.99
T COLD	12	5	12	76	16	0	60	7.55	10.26	0.37	0.30	3.61	4.97
P NORM	58	2	14	88	17	0	45	5.29	10.64	0.34	0.32	2.46	4.99
P ABNM	18	2	13	78	18	0	51	5.97	9.60	0.33	0.31	2.76	4.98
P WET	11	3	14	76	6	0	65	8.04	9.33	0.38	0.29	3.86	4.98
P DRY	7	0	12	80	38	0	30	2.71	10.03	0.24	0.33	1.01	4.98
N 0	22	6	43	84	13	0	41	5.36	5.60	0.33	0.31	2.74	4.95
N 90	22	0	4	87	19	0	49	5.64	11.91	0.34	0.31	2.53	5.02
N 112	10	2	1	85	23	0	43	4.83	13.26	0.37	0.34	2.09	4.88
N 180	22	0	0	87	19	0	50	5.65	12.36	0.34	0.31	2.53	5.03

* not available

Final Progress Report
National Institute for Global Environmental Change

Submitted by Evan H. DeLucia, Head, Department of Plant Biology,
University of Illinois, on behalf of Dr. Ross Fitzhugh

Project Title:
Carbon and nitrogen dynamics and retention in an agricultural ecosystem under elevated atmospheric carbon dioxide and ozone

Principal Investigator:
Ross D. Fitzhugh
University of Illinois, Urbana, IL

Co-Investigator(s):
Valerie Eviner
Institute of Ecosystem Studies, Millbrook, NY

Rodney Venterea
USDA-ARS, St. Paul, MN

Funding (by Award Year):
AY 2004-2005 $179,003
AY 2005-2006 $163,629
AY 2006-2007 $109,940

Executive Summary:
Energy production is contributing to rising atmospheric CO_2 and O_3 concentrations. Changes in the concentrations of these gases may have dramatic effects on terrestrial ecosystems. Study of the effects of increases in CO_2 and O_3 on ecosystem C and N dynamics is important because these dynamics influence the sustainability of agricultural production as well as the off-site consequences of agricultural practices, including the pollution of surface and groundwater and soil-to-atmosphere gaseous emissions which contribute to the greenhouse effect. In this proposal, we study the effects of elevated CO_2 and O_3 on the cycling and retention of C and N in soybean/corn rotations in Illinois using free-air gas concentration enrichment (FACE) technology. These projected changes in atmospheric CO_2 and O_3 alter agroecosystem emissions of greenhouse gases. During the 2005 growing season, elevated CO_2 increased both CO_2 and N_2O emissions from soybean fields, while in the 2006 growing season, elevated CO_2 decreased N_2O emissions. Elevated CO_2 and O_3 concentrations also alter degradation of crop residues, but the nature of these effects vary depending on residue type.

Objectives:
The objectives of this project were to expose soybean and corn plots to ambient (control), enriched CO_2, elevated O_3, and simultaneously elevated CO_2 and O_3, using free-air gas concentration enrichment, and to measure the following:

1) crop residue quantity and quality
2) decomposition and C and N release from residue
3) hydrological and gaseous C and N losses
4) soil C and N mineralization and nitrification

Approach:
In this project, we studied the effects of elevated atmospheric CO_2 and O_3 on C and N dynamics in a corn/soybean ecosystem. Using a free-air gas concentration enrichment facility, twenty-four 20-m diameter plots were exposed to ambient, elevated CO_2 (550 ppm), elevated O_3 (80 ppb), or simultaneous CO_2 and O_3. The effects of changes in atmospheric chemistry on plant traits were evaluated by quantifying crop residue quantity and quality and labile C inputs to the soil. Mediation of ecosystem C and N dynamics by changes in plant traits were assessed by determining the rates of decomposition of crop residues, soil respiration, microbially mediated soil N fluxes, as well

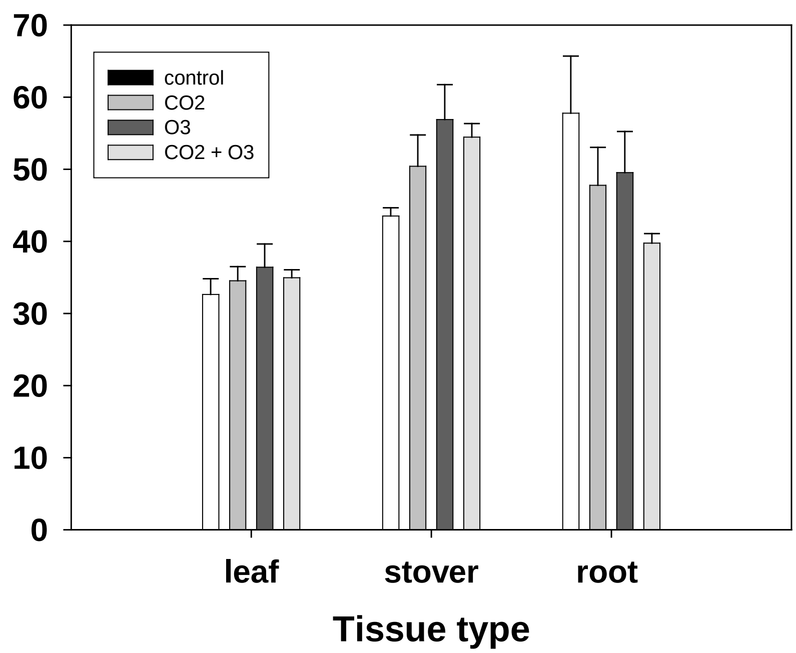
as hydrological and gaseous losses of C and N. This study provided the first field-scale evaluation of the effects of atmospheric CO_2 and O_3 on N retention and loss in agricultural ecosystems of the midwestern US.

Results to Date:

Litter chemistry

As reported last year, the quality of soybean litter collected following the 2005 season exhibited some trends although no results were statistically significant (Figure 1). Exposure to elevated atmospheric CO_2 and O_3, alone, tended to result in increased stover C/N by decreasing litter %N. In contrast, elevated atmospheric CO_2 and O_3 tended to result in decreased root C/N due to decreased C and increased N.

Figure 1. Soybean litter C/N ratio for leaves, stover, and roots exposed to different atmospheric treatments.



Litter mass loss

Soybean leaves from each treatment, incubated under those treatment conditions for 6 months, showed significant differences in mass loss ($p=0.016$, Figure 2). Control conditions had the lowest mass loss, followed by the combination of elevated CO_2 and O_3. Singly, elevated CO_2 and elevated O_3 enhanced litter mass loss. Since soybean leaf litter did not significantly differ across treatments (Figure 1), it is assumed that these effects are mediated by differences in plot conditions across sites. In contrast, soybean stover, which did significantly differ in litter chemistry across treatments (Figure 1), did not show any treatment differences in litter mass loss ($p= 0.50$, data not shown).

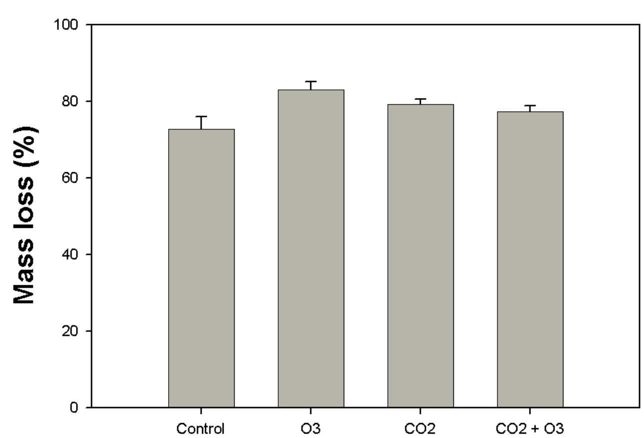


Figure 2. Litter mass loss of soybean leaves, from each treatment, incubated under each treatment.

To test the impacts of treatment-induced plot conditions on litter mass loss, independent of treatment effects on litter chemistry, common litter types were incubated under the following conditions:

- Soybean exposed to control conditions, elevated CO_2, elevated O_3, and elevated CO_2 and O_3.
- Corn exposed to control conditions and elevated CO_2 (corn was not treated with O_3).

Leaves, stover and roots from both corn and soybean were incubated under these 6 conditions, this litter was taken from untreated fields. In general, most tissue types decomposed faster in corn fields than in soybean fields (Figure 3-7). A common soybean leaf litter decomposed faster in corn than in soybean plots ($p=0.006$), except for soybean grown under elevated CO_2. Within soybean treatments, litter incubating under elevated CO_2 decomposed faster than the same litter in control plots (Figure 3). In contrast, a common soybean stover decomposed faster when exposed to elevated O_3, and especially when exposed to elevated CO_2 and O_3 (Figure 4). A common root litter, incubated in each of these treatments, showed no difference in litter mass loss (data not shown).

Figure 3. Control soybean leaf litter incubating for 6 months under different treatments.

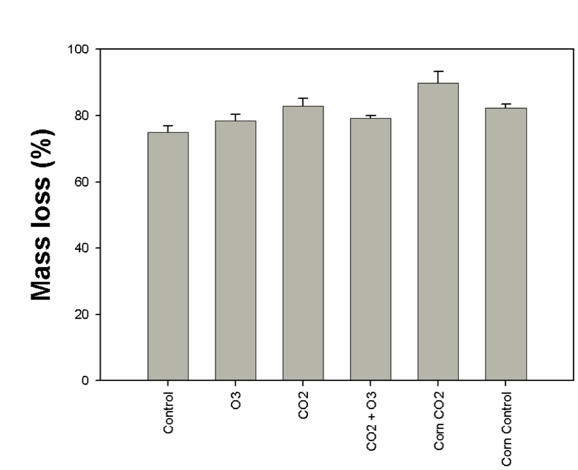
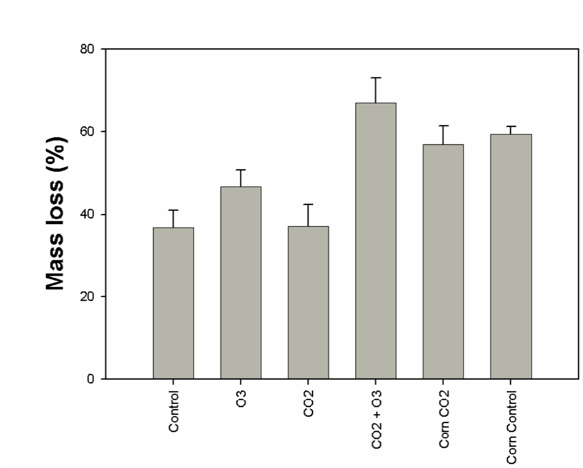


Figure 4. Control soybean stover litter incubating for 6 months under different treatments.



When a common corn litter was incubated under different plot conditions, again, litter mass loss rates tended to be faster in corn than in soybean plots. The common corn leaf litter decomposed most slowly in soybean plots exposed to elevated O_3 (Figure 5), and corn stover showed the same general pattern (Figure 6).

Figure 5. Control corn leaf litter incubating for 6 months under different treatments.

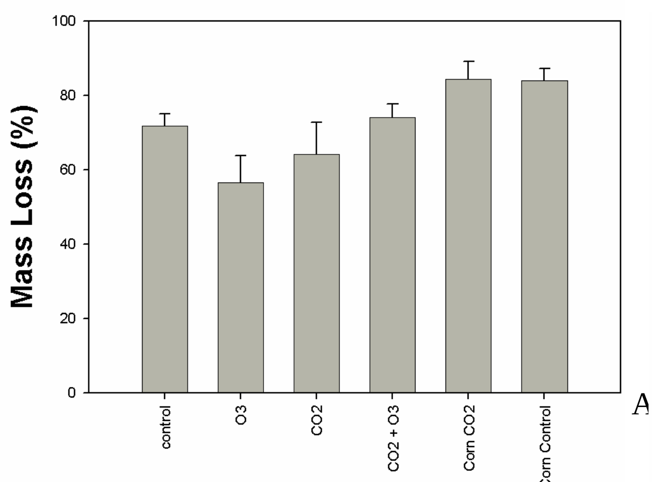


Figure 6. Control corn stover litter incubating for 6 months under different treatments.

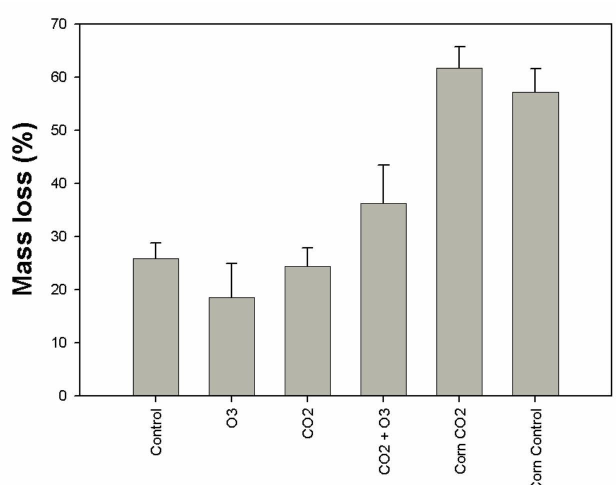
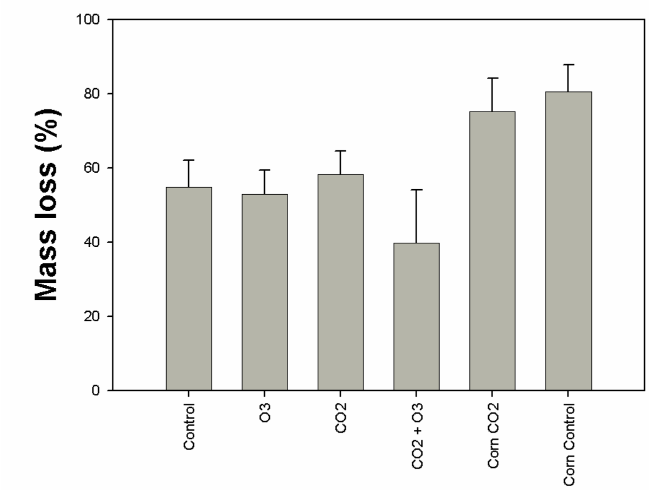


Figure 7. Control corn root litter incubating for 6 months under different treatments



Corn roots decomposed fastest in corn plots, but CO_2 and O_3 treatments did not alter its decomposition patterns (Figure 7).

Overall, it appears that CO_2 and O_3 treatments had marked impacts on litter mass loss, but due to changes in the decomposing environment (Figures 3-7), rather than through changes on litter chemistry. We are currently carrying out an incubation of the treatment litter under common conditions to finish teasing this apart. In addition, we are processing litter mass loss from litter collected and incubated at the end of the 2006 growing season, through the end of the 2007 growing season.

In addition to mass loss, litter is currently being analyzed for C and N loss patterns. This data is currently being analyzed, and for information on future publications contact Valerie Eviner.

Soil gas fluxes

Soil-to-atmosphere fluxes of N_2O also responded to the global change treatments in soybeans. In the 2005 field season, mean fluxes of N_2O were significantly greater under elevated atmospheric CO_2 than under elevated O_3, and this occurred largely in the latter part of the growing season. However, we saw the opposite pattern in 2006, with elevated CO_2 decreasing soil N_2O fluxes, particularly in the early season. No significant trends were found during the 2006 corn field season.

Figure 8. Soil N_2O fluxes in 2005 versus 2006 from soybean fields exposed to elevated or ambient CO_2.

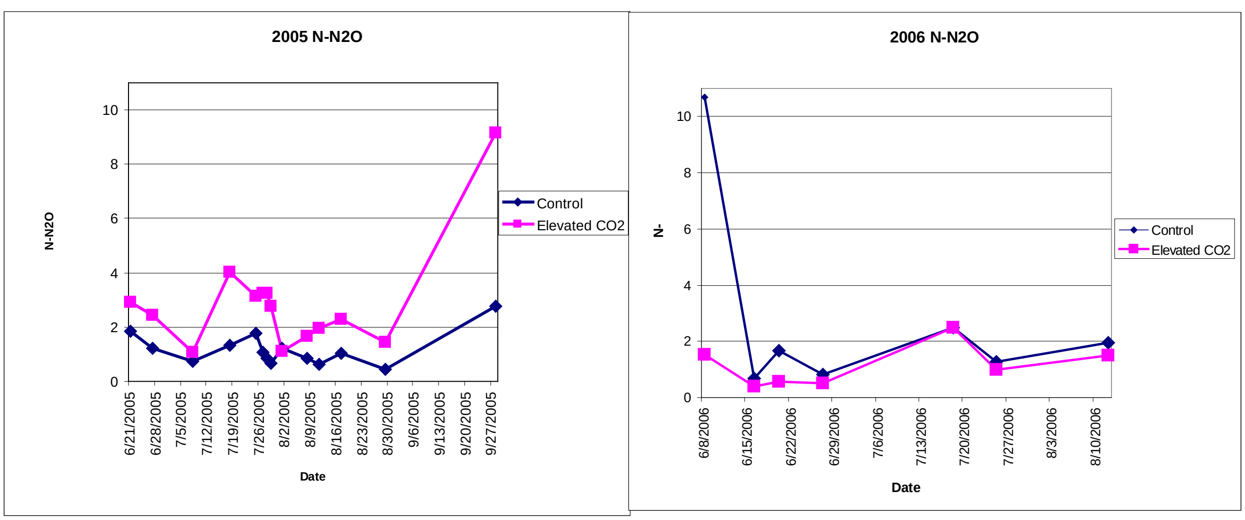
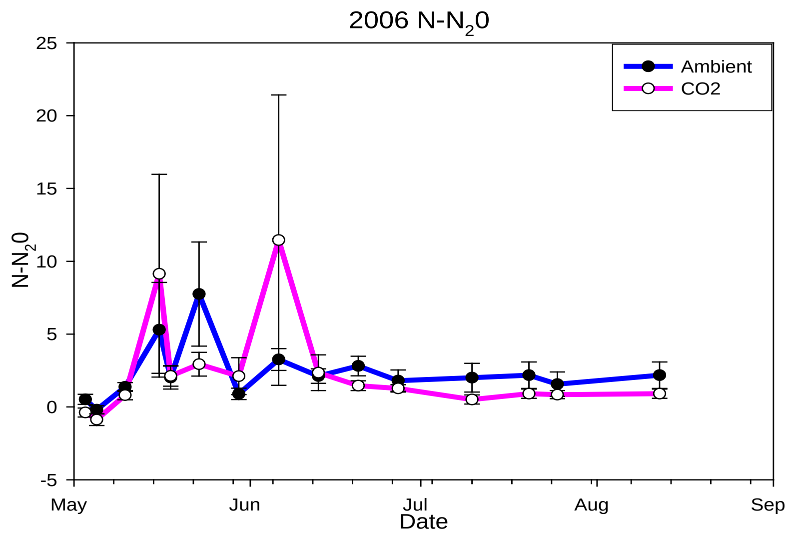


Figure 9. Soil N_2O fluxes in 2006 from corn fields exposed to elevated or ambient CO_2.



Nitrification and Nitrogen Mineralization

Soil nitrate (NO_3^-) and ammonium (NH_4^+) concentrations did not show significant responses to global change treatments. During the 2005 field season, NO_3^- concentrations in the control plots were significantly higher than the CO_2+O_3 and the O_3 plots but this was likely the result of an outlier in the control plot. Plot 4, one of the control plots, was significantly different as a result of previous usage history. Plot 4 was originally used as a cattle feed which could lead to increased levels of NO_3^- and phosphorous, which could also explain the slightly elevated level of NO_3^- in plot 3.

Figure 10. 2005 soil NO_3^- concentrations by treatment

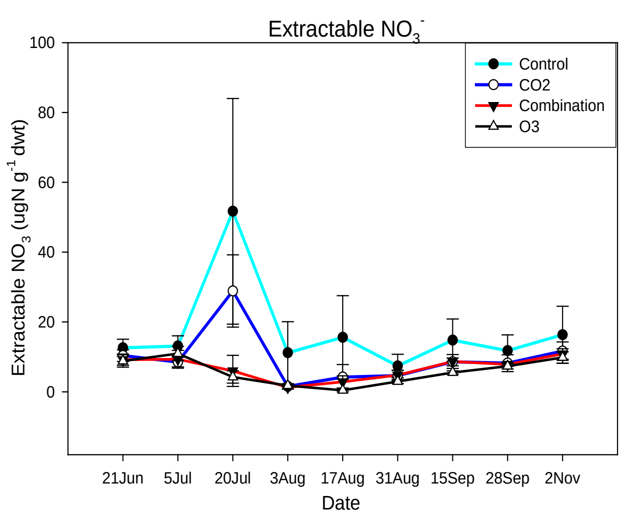
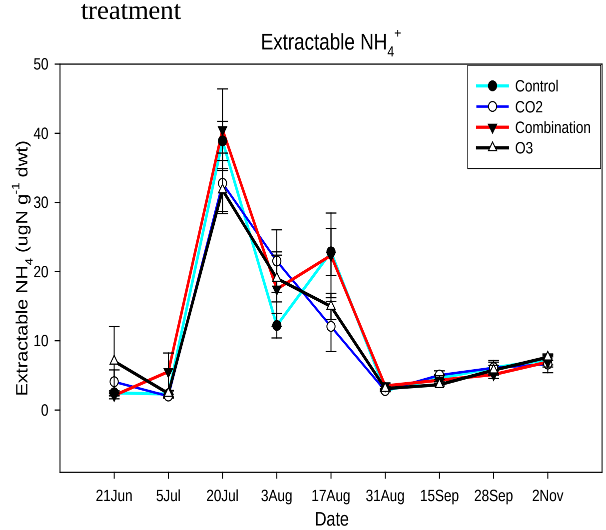


Figure 11. 2005 soil NH_4^+ concentrations by treatment



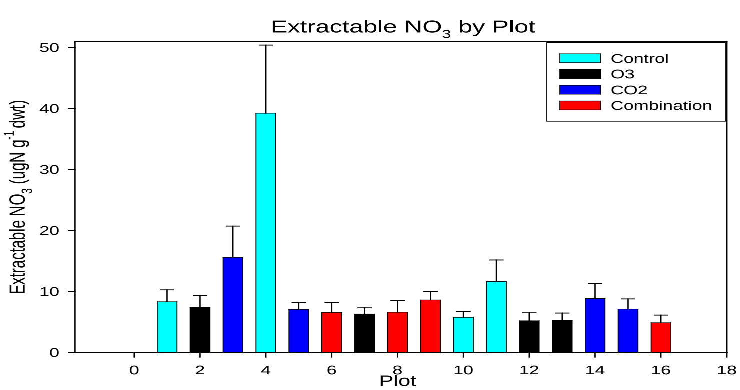


Figure 12. Soil NO_3^- concentrations for the duration of the 2005 field season exposed to elevated CO_2, O_3, CO_2+O_3, and ambient conditions in each of the 16 rings.

No significant differences were seen in the rates of nitrogen mineralization or nitrification in the study. Both net nitrification and N mineralization showed similar patterns, with high rates early in the growing season and the rates steadily decreasing as the year progresses.

Figure 12. Nitrification in soils exposed to global change treatments.

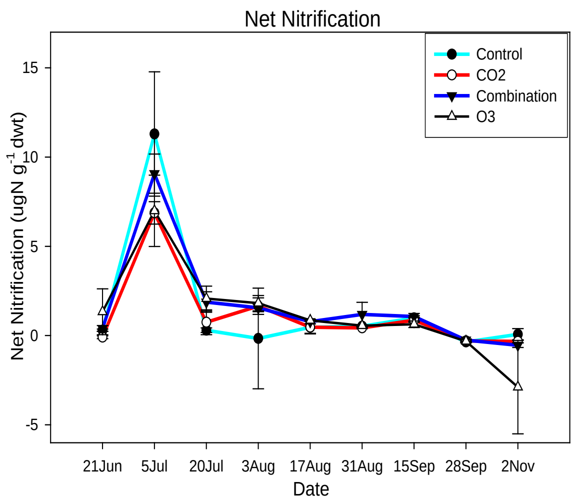
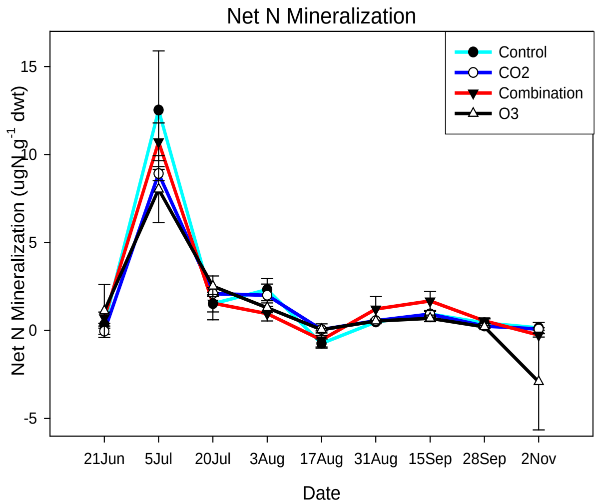


Figure 13. N mineralization in soils exposed to global change treatments.



Publications:
We have not yet published a peer-review article from this project. There are pending manuscripts at the current time with more expected early in 2009.

Hoorens B, Fitzhugh ED. Decomposition of crop residue in the soil: effects of global change mediated by plant roots. In preparation for Plant and Soil.
Hoorens B, Venterea R, Fitzhugh RD. Partitioning of sources of soil respiration under different global change treatments in a corn-soybean agro-ecosystem. In preparation for Plant and Soil.
Hoorens B, McGrath J, Leakey ABD. Global change impacts on trophic interactions: the response of anecic earthworm activity in a corn-soybean agro-ecosystem to Free-Air Concentration Enrichment of CO_2 and O_3. In preparation for Oecologia.

Presentations:
Hoorens B. A global meta-analysis of plant trait effects on litter decomposition. Vegetation Function Network Workshop (http://www.vegfunction.net/), Macquarie University, Sydney, Australia. *Invited Participant.*

Students receiving support from this grant:
Michael Masters, M.S. University of Illinois, May, 2008 (currently, Research Technician, Energy Bioscience Institute, UIUC)
Joshua Burke, M.S. University of Illinois, May, 2008 (currently, Research Technician, Energy Bioscience Institute, UIUC)
Nicholas Morphew, M.S. University of Illinois, May 2008 (currently, Laboratory Coordinator, School if Integrative Biology, UIUC)
Bart Hoorens, Postdoctoral Scientist (currently, Postdoctoral Scientist, Vrije Universiteit, The Netherlands)
Fenmeng Zhu, Postdoctoral Scientist (currently, Postdoctoral Scientist, University of California Davis)

Thesis:
Morphew N, Venterea R, Fitzhugh RD. Analysis of a corn-soybean nitrogen budget and the effect of elevated CO2 on nitrous oxide emissions from denitrification. 2008.

NICCR Final Report

Project title: Net Ecosystem Carbon and Water Vapor Exchange of Tallgrass Prairie: Component Fluxes and Spatial Heterogeneity

End Date: 9/14/07

Principal investigator/Co-investigator

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Abstract

Changes in climate could impact the carbon balance of tallgrass pairie as well as the sustainability of the ranching economy in the central US. Unfortunately, the prairie landscape in eastern KS is complex; composed of uplands, rocky slopes, and convoluted drainages. This makes measuring the carbon balance difficult. A study was conducted on grassland watersheds near Manhattan, KS to determine how CO_2 emissions from soil (soil respiration) varied in space and time. The goal was to develop techniques for improved measurement and modeling. Results showed fivefold variation in CO_2 emissions depending on measurement location. However, the relationships between measurement sites (rank on a given day) tended to stay constant over time. Thus, it may be possible to make measurements at a few key locations and estimate soil respiration for an entire watershed. This could be a powerful tool for studying climate change and land management impacts on grasslands at larger scales.

Research Activities

Background:

Soil respiration is a major component of the carbon balance in the native grass prairie ecosystem that extends across the Flint Hills of eastern Kansas. The native vegetation, mainly C4 warm season grasses, retains a large fraction of total biomass below ground (up to 70 %) creating rapid and abundant biogeochemical cycling of carbon in the rhizosphere. However, measuring and modeling soil respiration is challenging because the geomorphology of the Flint Hills landscape inherently creates spatial variations in above- and below-ground environmental conditions. This spatial variability, especially in soil moisture, translates into marked disparity in soil respiration at different landscape positions. Large temporal variations in soil respiration are also common because fluxes are influenced by seasonal growth, grazing, prescribed burning, and the patterns of precipitation. In summary, more information is needed on the spatial heterogeneity and temporal patterns of soil respiration from tallgrass prairie so that better measurement strategies and models can be developed. This information is needed so carbon fluxes can ultimately be estimated at the watershed or pasture scale (i.e., the same scales where management decisions are made).

The concept of *rank stability*, sometimes termed *temporal stability*, may prove useful when attempting to quantify spatial variations in soil respiration in tallgrass prairie. If fluxes at different locations on the landscape tend to maintain the same relative rank on different measurement dates (i.e., fluxes at certain locations always being higher than the rest or lower than the rest - regardless of measurement date and conditions), then there may be an inherent rank distribution. Once this distribution is known, it may be possible to predict fluxes for the whole landscape using data collected at only a few key locations. Furthermore, rank stability can be very helpful when modeling fluxes or using remote sensed data as a part of the flux estimate process. Unfortunately, it was not know if soil respiration demonstrated rank stability in our ecosystem.

Main Objectives:

- *measure the spatial and temporal variation in soil respiration across the tallgrass prairie landscape*
- *determine if the relationship among the measurement locations demonstrated rank stability over the growing season.*

Methods:

Experiments were conducted on the Rannells Flint Hills Prairie and Konza Prairie Biological station south of Manhattan, KS, USA (39.11^{o}N,96.34^{o}W). Vegetation was tallgrass prairie, dominated by the C_4 grasses, *Andropogon gerardii* Vitman and *Sorghastrum nutans* (L.) Nash. Soils in the area are transitional from Ustolls to Udolls and include deep well-developed silt loam and silty clay loam soils as well as soils with varying amount of limestone and chert fragments with soil depths from 10-200 cm above consolidated limestone. Fire has occurred annually for at least the past 100 years and that has essentially eliminated the C_3 grass population and most woody species. Both sites had been annually burned for over 20 years and burned in April in both years of the study. The 30-year average annual precipitation is 840 mm, with 520 mm occurring during the growing season.

Soil respiration was measured on three sampling transects: a 405-m 28 station sampling transect on the Konza Prairie (KZ), a 405-m, 28-station sampling transect on the Rannells

Prairie (R1), and a 180-m, 13-station sampling transect on the Rannells Prairie (R2). There are significant variations in topography along these transects with elevations changes as great as 15 m and slopes sometimes exceeding 15 degrees (Figs. 1 to3). Soil-surface CO_2 flux was measured along each transect on weekly or bi-weekly intervals between 1030 and 1300 LST using a portable Li-Cor 8100 non-steady state chamber system (Li-Cor Inc., Lincoln, NE). The chamber was 10.3 cm m in diameter with a total volume of 955 cm^3. Soil collars made from PVC (7 cm tall) were permanently installed at each sampling site on the transects to insure that the same point was sampled on each measurement day. The height of each collar (portion extending above ground) was measured on each sampling day and used to adjust the flux calculation for the correct system volume. During each CO_2 measurement, soil temperature at 10 cm was measured. Data were collected from mid May through September on both years. In total, approximately 1690 individual flux measurements were made.

Statistical analysis included tests for temporal stability of spatial patterns both within and between sequential sampling dates, including Spearman's rank correlation and relative differencing techniques. A difficulty associated with conducting the temporal stability analysis was that soil respiration follows a strong diurnal pattern and the measurements along the longer transect took over 2 hours to complete. Thus, to compare readings, data were adjusted (i.e., detrended) to predict CO_2 from each sample sites at a given moment in time (e.g., 11:00 LST). To accomplish this task certain collars were read twice, once at the beginning and again at the end of the sampling period.

Additional research was conducted to study small scale variations in soil surface CO_2 fluxes. Because the dominant vegetation types are bunch grasses, the surface is a patchwork of closely spaced grass crowns separated by areas of bare soil. The crowns typically cover about 25 to 30 % of the surface. However, the soil-surface CO_2 flux measurements on the three sampling transects were collected on patches of bare soil between the crowns (i.e., where a collar could be installed that excluded all green vegetation). Soil respiration may be higher in the zone around the crown where root density, root exudates, and microbial biomass are greater. Thus, the measurements on the transects may have slightly underestimated the areal soil respiration. Sets of paired collars were installed near transect R1. One collar was placed directly over a crown and the second collar installed less than 10 cm away on bare soil. On several dates during the growing season, fluxes were measured from the bare-soil collar and the crown-collar with vegetation with the LI-8100 system. The leaves from the crown-collar were then immediately removed by clipping and flux was measured again. Comparing these three measurements provided a measure of soil-surface flux from the bare and crown areas as well as a measure of canopy respiration.

Research Highlights

Precipitation was below normal in the spring of 2006 and above normal in the spring of 2007 (Fig. 1). As a result, there was greater biomass in the 2006 at all three transects, especially at Konza (Figs. 2 and 3). On the Konza transect, there was good correlation between and elevation, with greater biomass in the lowland landscape positions as would be expected in zones of deeper soils and greater water availability from drainage (Fig. 2). On Rannells transects R1 and R2; however, there was not good correlation between biomass and landscape position (Fig. 3). Greater small scale variations in biomass may have may have masked the effect the effect of elevation. Much more extensive sampling plans are needed when attempting to evaluate the effect of landscape position on growth.

Figures 4 to 6 show the season trends in soil respiration as averaged over the entire transect. The increases in flux in the early spring are mainly caused by increasing canopy photosynthesis (increasing LAI) and increasing temperature. Temporal variations later in the season are mainly caused by changes in soil moisture as affected by patterns in precipitation. As can be seen by errors bars, standard deviations were quite large (1.5 to 3 μmol m^{-2} s^{-1}) when computed over the transect. A 95 % confidence interval around the means as computed from two standard errors ranged from ± (1 to 2 μmol m^{-2} s^{-1}) on the 28-station transects. A simple mean flux computed from a grid or transect sampling scheme can estimate watershed scale fluxes to within ± 20 to 25 % under the best of circumstances.

Figure 7 shows an example of the spatial variation in fluxes along the Konza transect in July of 2006. Fluxes tended to be inversely related to elevation, however; there were uncharacteristically low fluxes between 185 and 225 m. This demonstrates how small scale variations in flux, likely caused by small scale soil or plant variations, can mask topographic effects. In future efforts it is recommended to measure fluxes at several adjacent locations (a cluster of points) at each topographic position to quantify how small scale variation affects fluxes. Figures 7 and 8 show fluxes from each sampling location were averaged over the growing season. There was over a two fold variation in flux along the transects even when averaged over time. Also, the Konza and R2 transects show the same spatial patterns in both years; a strong sign of rank stability. Spatial patterns along transect R1 were not highly correlated between years, but this transect had more uniform vegetation and less pronounced elevation changes (Fig. 3).

The spatial variation in soil CO_2 flux along the transects was very large within a given measurement day. Figure 7 shows an example from Konza where fluxes ranged from 2 to 11 μmol m^{-2} s^{-1}, and sometimes demonstrated large variations in flux between adjacent collars (e.g., 150-200 m).

Matrices of the Spearman rank correlation coefficients by transect by year are shown in Tables 1 to 6. Correlations were the highest for Transect R2 on both years, with most coefficients greater than 0.5 (Tables 5 and 6) - a sign of strong rank stability. Recall Transect R2 was the location with the greatest variation in topography and vegetation. The correlations coefficients were lower for the Konza Transect and lowest on Transect R1. Thus, the degree of rank stability was related to degree of the elevation change and variations in soil depth on the transect. Clearly, rank stability is low when there is a lot of uniformity on the transect where small scale spatial variations and small measurement errors have a greater impact on results. Example mean relative difference plots showed that there were very large variations in flux along transects on a given day, and that collars having similar fluxes may have been located an very dissimilar locations along the transect.

Rank/temporal variability in soil respiration was clearly demonstrated on tallgrass prairie. This was expected because soil water content and primary productivity, factors that strongly govern soil respiration, and are known to be rank stable in many landscapes. Data suggest that should be possible to estimate soil respiration at the watershed scale using chamber measurements at a few key locations on the landscape – locations that would allow the monotonic rank function to be approximated. Remote sensing, GIS, and modeling tools would be need to be combined to achieve this goal at large scales.

Small Scale Spatial Variation: The importance of soil surface CO_2 fluxes near the crown

The tallgrass prairie is dominated by two perennial bunch grasses, Big Bluestem and Indian Grass. Thus, the soil surface is a mixture of grasses originating from small hills or crowns with patches of bare soil in between each cluster of tillers. As mentioned in the methods, a study was performed to compare soil-surface respiration from the soil adjacent to the grass crowns with that from bare soil patches between crowns. Figure 10 shows data from a preliminary attempt to make this comparison. Two soil collars were placed in seven measurement locations, one collar included a crown (labeled collar A) and the other collar encompassed bare soil (labeled B). Once during the summer, all A collars were measured, clipped, and measured again to determine the difference in respiration due to the presence of leaves. These numbers were compared to the measurements from the B collars, taken in between the A collar measurements. On average, soil respiration was 17% greater near the crown. Other studies showed even larger differences. Data suggests that making soil respiration measurements solely on the bare soil patches between crowns may underestimate the areal soil-surface CO_2 flux in tallgrass prairie.

Research Products

Publications

We expect at least two peer reviewed publications from this project. One is completed and in the process of internal review (a chapter from a Ph.D. dissertation) and a second is still in preparation.

Student Degrees Supported

We had two Ph.D. students that received partial support from this project.

Murphy, John Thomas. 2007. Patterns of carbon dioxide and water vapor flux following harvest of tallgrass prairie at different times throughout the growing season. Ph.D. Dissertation. Kansas State University, Manhattan, KS. `http://hdl.handle.net/2097/342`

Duesterhaus, Jamey L., 2008. A micrometeorology study of stock watering ponds, rangelands, and woodlands in the Flint Hills of Kansas. Ph.D. Dissertation. Kansas State University, Manhattan, KS. `http://hdl.handle.net/2097/864`

Table 1. Matrix of Spearman rank correlations for soil respiration measurements collected on 14 dates in 2006. Data represent the rank correlation of 28 locations on the 405-m long transect KZ on Konza Biological Prairie Station. Missing data for dates 3, 4, 5, and 12 were derived from each location's seasonal average rank, and then used to compute Spearman ranks.

Dates:		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	DOY:	138	145	159	170	177	188	193	201	213	219	228	235	248	257
(1)	138	1.000													
(2)	145	0.581	1.000												
(3)	159	0.447	0.379	1.000											
(4)	170	0.558	0.570	0.522	1.000										
(5)	177	0.495	0.411	0.266	0.539	1.000									
(6)	188	0.553	0.386	0.271	0.734	0.294	1.000								
(7)	193	0.530	0.339	0.352	0.564	0.514	0.610	1.000							
(8)	201	0.443	0.332	0.459	0.793	0.593	0.694	0.552	1.000						
(9)	213	0.116	0.327	0.301	0.676	0.293	0.621	0.182	0.724	1.000					
(10)	219	0.423	0.571	0.571	0.841	0.429	0.666	0.512	0.808	0.740	1.000				
(11)	228	0.216	0.156	0.253	0.179	0.031	0.062	0.273	0.245	0.206	0.255	1.000			
(12)	235	*0.349*	*0.234*	0.255	0.121	-0.107	*0.276*	*0.287*	*0.248*	*0.089*	*0.158*	*0.637*	1.000		
(13)	248	0.559	0.322	0.214	0.297	0.204	0.534	0.575	0.302	-0.010	0.173	-0.032	*0.292*	1.000	
(14)	257	0.654	0.325	0.356	0.281	0.270	0.436	0.470	0.330	0.188	0.286	0.161	*0.500*	0.688	1.000

Table 2. Matrix of Spearman rank correlations for soil respiration measurements collected on 13 dates in 2007. Data represent the rank correlation of 28 locations on the 405-m long transect KZ on Konza Biological Prairie Station.

Dates:		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	DOY:	156	171	177	184	191	197	208	215	222	227	234	249	260
(1)	156	1.000												
(2)	171	0.580	1.000											
(3)	177	0.607	0.719	1.000										
(4)	184	0.540	0.560	0.885	1.000									
(5)	191	0.291	0.506	0.592	0.679	1.000								
(6)	197	-0.027	0.274	0.360	0.537	0.790	1.000							
(7)	208	-0.027	0.321	0.300	0.459	0.771	0.784	1.000						
(8)	215	0.427	0.339	0.310	0.486	0.525	0.558	0.514	1.000					
(9)	222	0.071	0.118	0.090	0.282	0.485	0.652	0.602	0.787	1.000				
(10)	227	0.140	0.077	0.213	0.379	0.345	0.486	0.433	0.639	0.875	1.000			
(11)	234	-0.048	0.332	0.346	0.476	0.644	0.829	0.794	0.500	0.693	0.573	1.000		
(12)	249	-0.057	0.306	0.302	0.452	0.673	0.866	0.793	0.610	0.787	0.594	0.939	1.000	
(13)	260	0.170	0.429	0.371	0.363	0.123	0.252	0.204	0.386	0.409	0.502	0.547	0.453	1.000

Table 3. Matrix of Spearman rank correlations for soil respiration measurements collected on 16 dates in 2006. Data represent the rank correlation of 28 locations on the 405-m long transect R1 on Rannells Flint Hills Prairie Preserve. Missing data for dates 3, 7, and 8 were derived from each location's seasonal average rank, and then used to compute Spearman ranks.

Date s:		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	DOY:	137	144	156	165	178	186	194	199	205	214	221	227	237	242	250	256
(1)	137	**1.000**															
(2)	144	**0.492**	**1.000**														
(3)	156	**0.111**	**0.485**	**1.000**													
(4)	165	**-0.210**	**0.375**	**0.545**	**1.000**												
(5)	178	**0.290**	**0.614**	**0.181**	**0.399**	**1.000**											
(6)	186	**0.384**	**0.384**	**0.085**	**0.005**	**0.431**	**1.000**										
(7)	194	**0.262**	**0.384**	**0.237**	**0.439**	**0.773**	**0.586**	**1.000**									
(8)	199	**0.319**	**0.619**	**0.083**	**0.440**	**0.682**	**0.465**	**0.544**	**1.000**								
(9)	205	**-0.083**	**0.195**	**0.180**	**0.608**	**0.631**	**0.158**	**0.590**	**0.429**	**1.000**							
(10)	214	**-0.018**	**0.363**	**0.085**	**0.489**	**0.766**	**0.360**	**0.653**	**0.574**	**0.831**	**1.000**						
(11)	221	**0.008**	**0.371**	**0.013**	**0.465**	**0.783**	**0.350**	**0.632**	**0.603**	**0.822**	**0.924**	**1.000**					
(12)	227	**0.073**	**-0.021**	**-0.042**	**0.111**	**0.304**	**0.121**	**0.288**	**0.282**	**0.287**	**0.123**	**0.268**	**1.000**				
(13)	237	**0.304**	**0.236**	**0.244**	**-0.028**	**0.281**	**0.495**	**0.506**	**0.215**	**0.015**	**0.242**	**0.090**	**-0.126**	**1.000**			
(14)	242	**-0.037**	**0.207**	**0.020**	**0.161**	**0.584**	**0.640**	**0.663**	**0.402**	**0.433**	**0.536**	**0.525**	**0.412**	**0.392**	**1.000**		
(15)	250	**0.175**	**0.250**	**0.230**	**0.093**	**0.375**	**0.259**	**0.439**	**0.027**	**0.002**	**0.181**	**0.099**	**-0.103**	**0.485**	**0.208**	**1.000**	
(16)	256	**-0.039**	**0.032**	**0.189**	**0.315**	**0.273**	**0.354**	**0.543**	**0.259**	**0.144**	**0.251**	**0.184**	**0.325**	**0.371**	**0.445**	**0.354**	**1.000**

Table 4. Matrix of Spearman rank correlations for soil respiration measurements collected on 11 dates in 2007. Data represent the rank correlation of 28 locations on the 405-m long transect R1 on Rannells Flint Hills Prairie Preserve.

Dates:		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	DOY:	155	162	176	187	192	198	207	222	226	243	255
(1)	155	**1.000**										
(2)	162	**0.103**	**1.000**									
(3)	176	**0.401**	**0.599**	**1.000**								
(4)	187	**0.494**	**0.371**	**0.773**	**1.000**							
(5)	192	**0.344**	**0.412**	**0.362**	**0.527**	**1.000**						
(6)	198	**0.506**	**0.260**	**0.435**	**0.558**	**0.357**	**1.000**					
(7)	207	**0.558**	**0.144**	**0.553**	**0.657**	**0.403**	**0.784**	**1.000**				
(8)	222	**-0.158**	**0.416**	**0.273**	**0.214**	**0.205**	**0.281**	**0.308**	**1.000**			
(9)	226	**-0.156**	**0.122**	**0.077**	**0.131**	**-0.081**	**0.547**	**0.409**	**0.552**	**1.000**		
(10)	243	**0.442**	**0.400**	**0.487**	**0.662**	**0.340**	**0.458**	**0.514**	**0.573**	**0.279**	**1.000**	
(11)	255	**0.612**	**0.362**	**0.612**	**0.704**	**0.347**	**0.401**	**0.587**	**0.287**	**0.143**	**0.717**	**1.000**

Table 5. Matrix of Spearman rank correlations for soil respiration measurements collected on 11 dates in 2006. Data represent the rank correlation of 13 locations on the 180-m long transect R2 on Rannells Flint Hills Prairie Preserve.

Dates:	DOY:	(1) 139	(2) 157	(3) 164	(4) 179	(5) 198	(6) 209	(7) 216	(8) 222	(9) 234	(10) 249	(11) 258
(1)	139	**1.000**										
(2)	157	**0.918**	**1.000**									
(3)	164	**0.841**	**0.626**	**1.000**								
(4)	179	**0.582**	**0.615**	**0.709**	**1.000**							
(5)	198	**0.588**	**0.588**	**0.841**	**0.830**	**1.000**						
(6)	209	**0.643**	**0.692**	**0.830**	**0.654**	**0.505**	**1.000**					
(7)	216	**0.736**	**0.560**	**0.835**	**0.429**	**0.703**	**0.879**	**1.000**				
(8)	222	**0.637**	**0.786**	**0.648**	**0.560**	**0.670**	**0.830**	**0.786**	**1.000**			
(9)	234	**0.901**	**0.775**	**0.912**	**0.808**	**0.791**	**0.269**	**0.786**	**0.269**	**1.000**		
(10)	249	**0.714**	**0.901**	**0.637**	**0.885**	**0.676**	**0.797**	**0.879**	**0.797**	**0.319**	**1.000**	
(11)	258	**0.852**	**0.890**	**0.725**	**0.709**	**0.896**	**0.621**	**0.830**	**0.621**	**0.335**	**0.786**	**1.000**

Table 6. Matrix of Spearman rank correlations for soil respiration measurements collected on 9 dates in 2007. Data represent the rank correlation of 13 locations on the 180-m long transect R2 on Rannells Flint Hills Prairie Preserve.

Dates:	DOY:	(1) 157	(2) 183	(3) 190	(4) 198	(5) 206	(6) 220	(7) 242	(8) 257	(9) 269
(1)	157	**1.000**								
(2)	183	**0.170**	**1.000**							
(3)	190	**0.335**	**0.962**	**1.000**						
(4)	198	**0.308**	**0.764**	**0.791**	**1.000**					
(5)	206	**0.599**	**0.555**	**0.709**	**0.495**	**1.000**				
(6)	220	**0.418**	**0.560**	**0.692**	**0.747**	**0.725**	**1.000**			
(7)	242	**0.423**	**0.692**	**0.780**	**0.775**	**0.637**	**0.780**	**1.000**		
(8)	257	**0.308**	**0.852**	**0.868**	**0.659**	**0.676**	**0.533**	**0.841**	**1.000**	
(9)	269	**0.473**	**0.797**	**0.830**	**0.775**	**0.659**	**0.676**	**0.720**	**0.802**	**1.000**

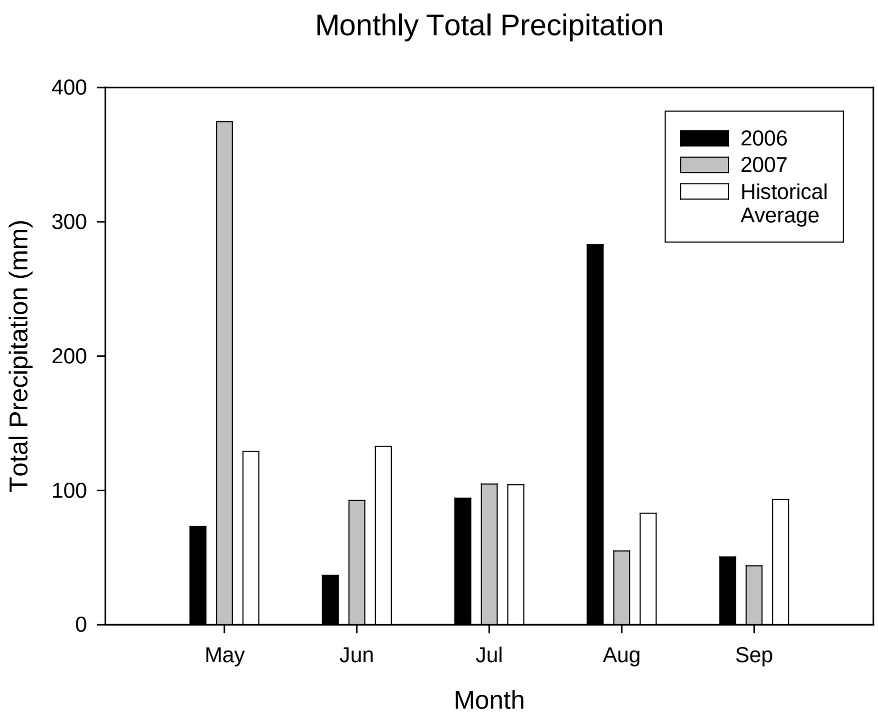


Figure 1. Monthly precipitation in 2006 and 2007 compared to the historical average.

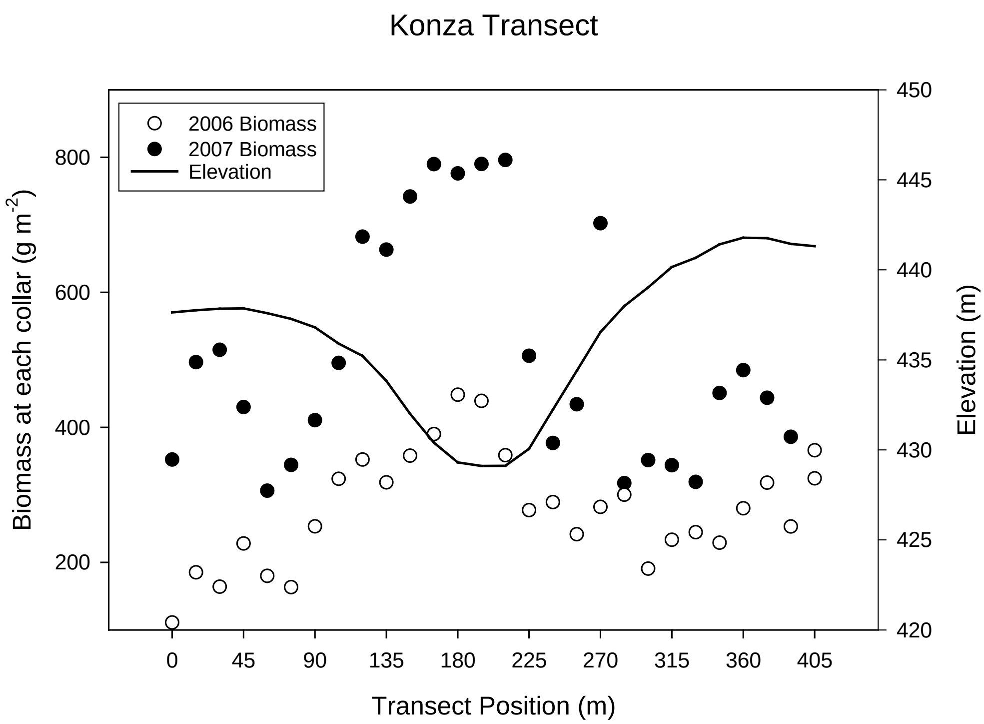
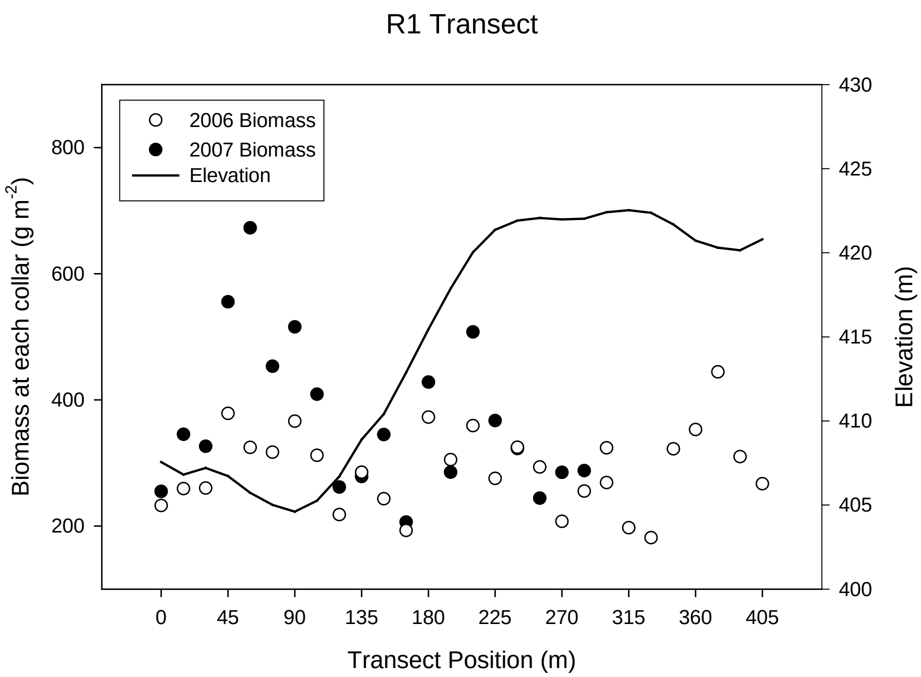


Figure 2. Biomass at each sampling location on the Konza Prairie transect. Data were collected on July 18 – 21 in 2006 and on August 6 -8 in 2007. Also shown is the change in elevation along the transect.



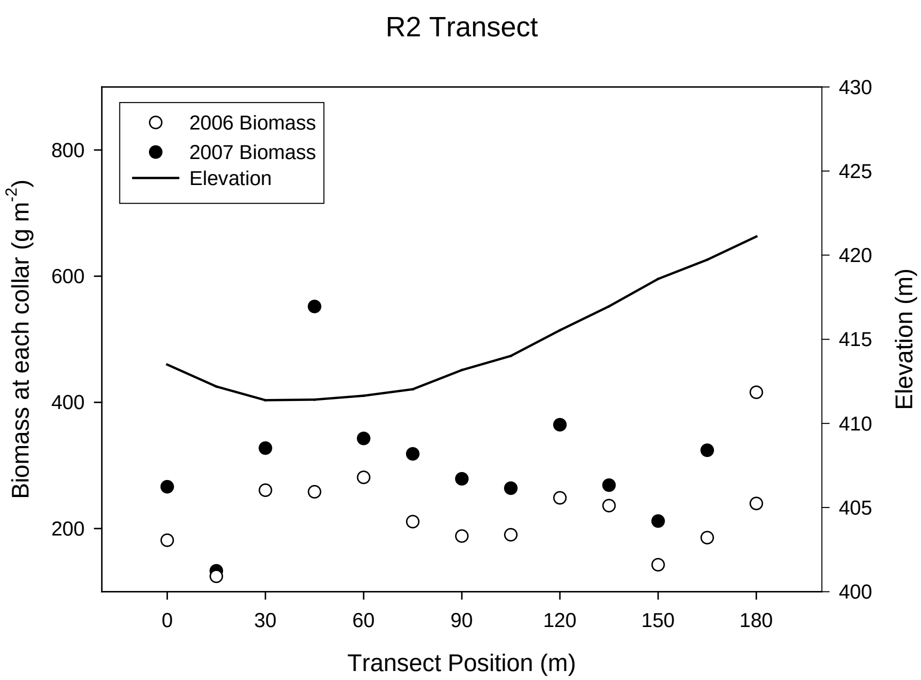
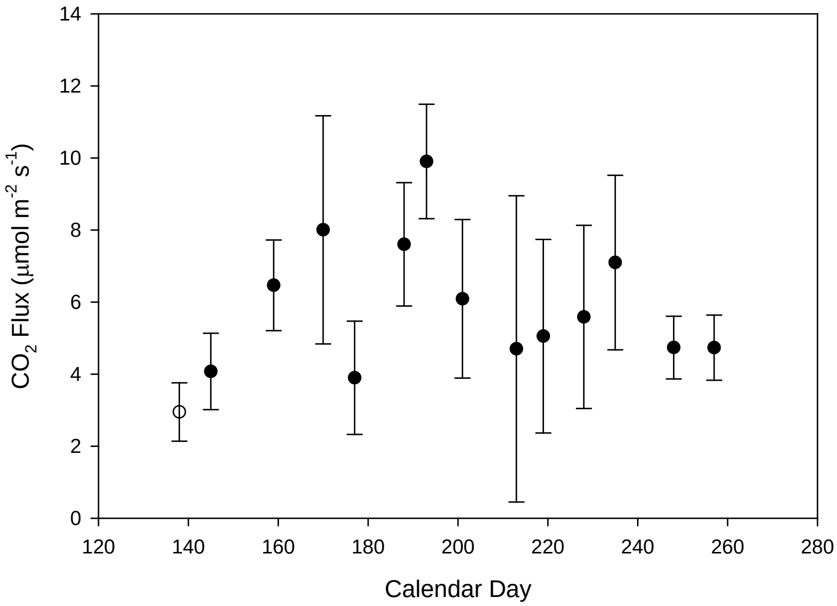


Figure 3. Peak biomass at each sampling location on the Rannell Prairie transects R1 and R2. Data were collected on July 18 – 21 in 2006 and on August 6 -8 in 2007. Also shown is the change in elevation along the transect.

KZ, Average Transect Flux for each sampling date, 2006



KZ, Average Transect Flux for each sampling date, 2007

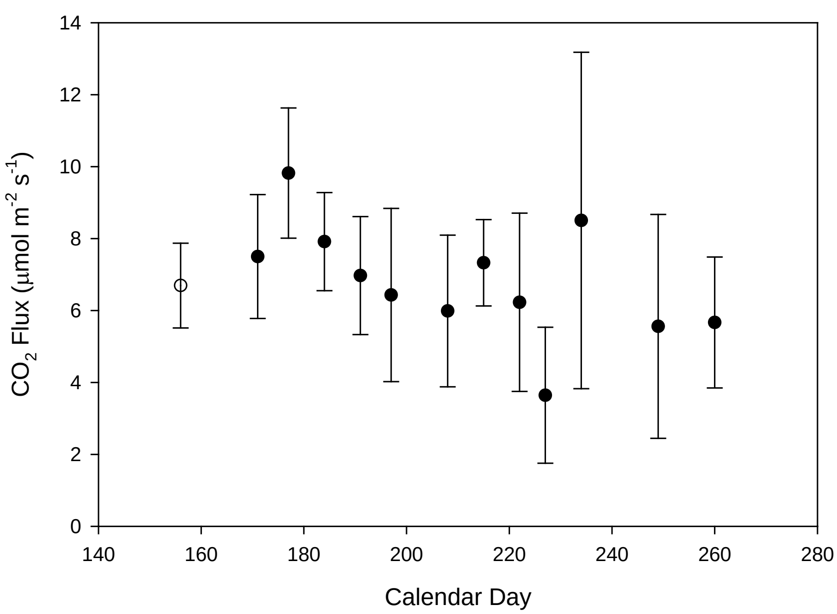
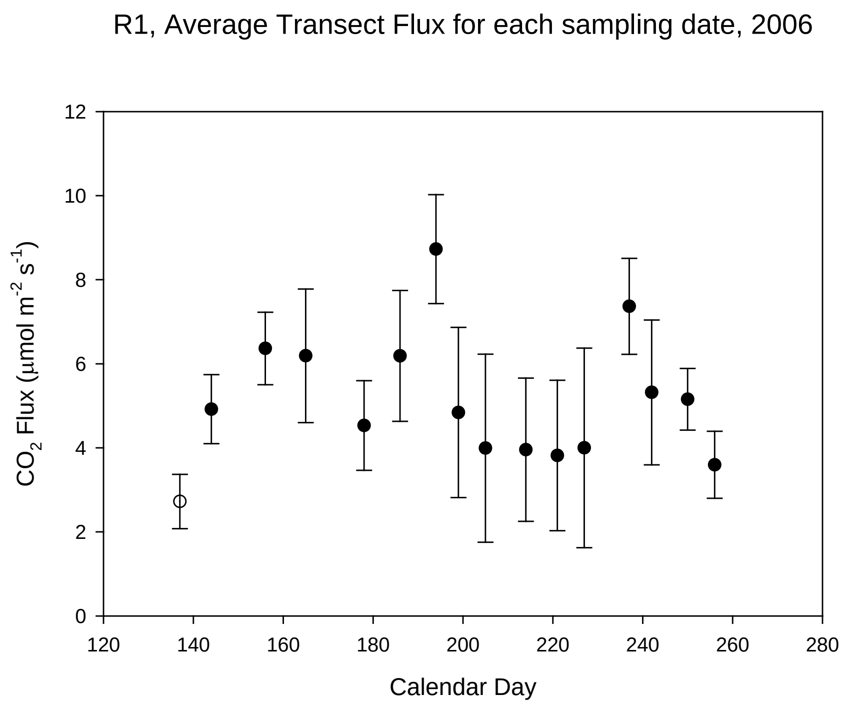


Figure 4. Seasonal patterns of average soil-surface CO_2 flux from transect on the Konza Prairie in 2006 and 2007. Data (mean ± 1 S.E.) were averaged over all 28 sampling locations on the transect



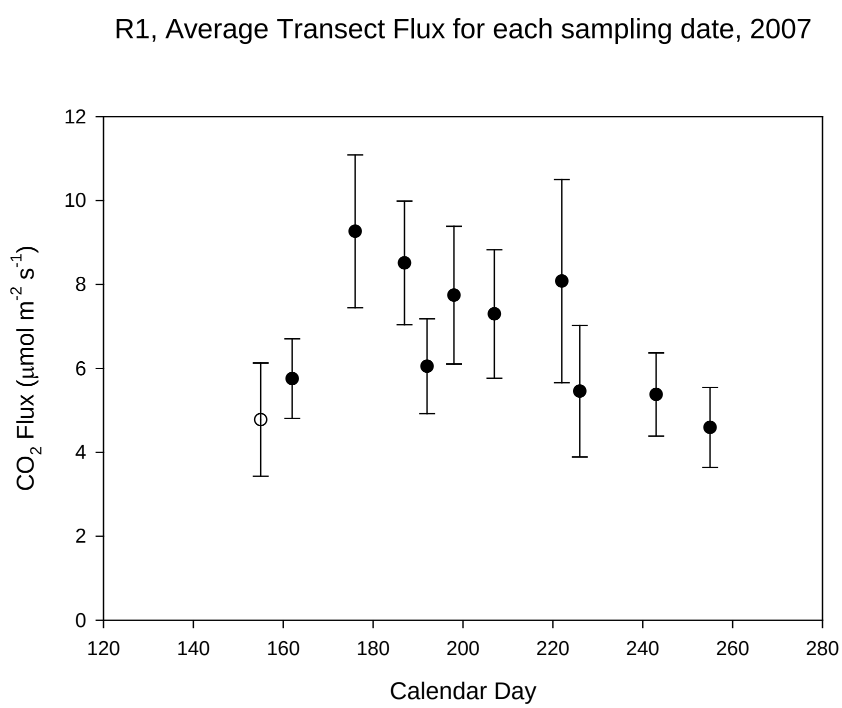
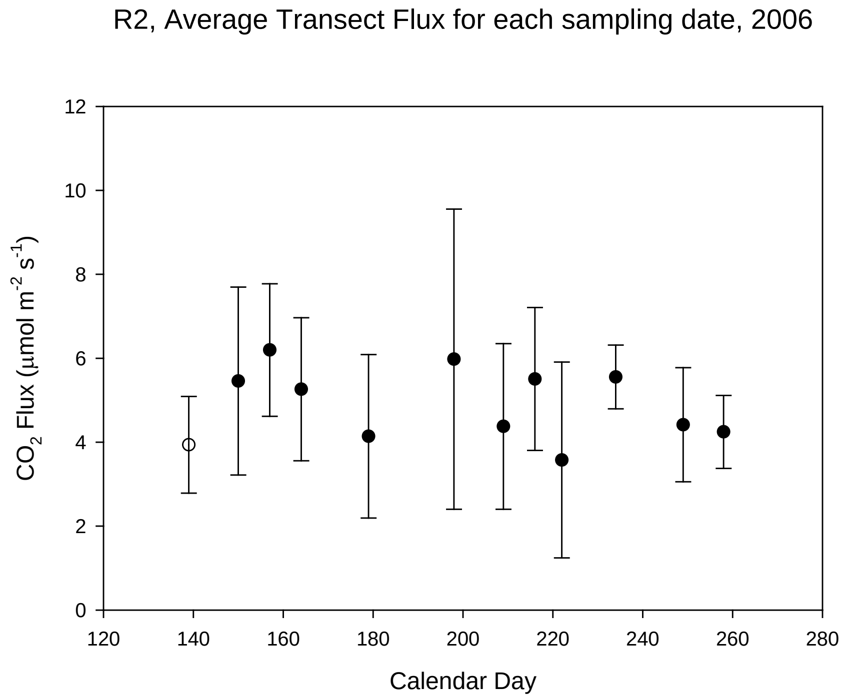


Figure 5. Seasonal pattern of average soil-surface CO_2 flux from transect R1 on the Rannells Prairie in 2006 and 2007 . Data (mean ± 1 S.E.) were averaged over all 28 sampling locations on the transect



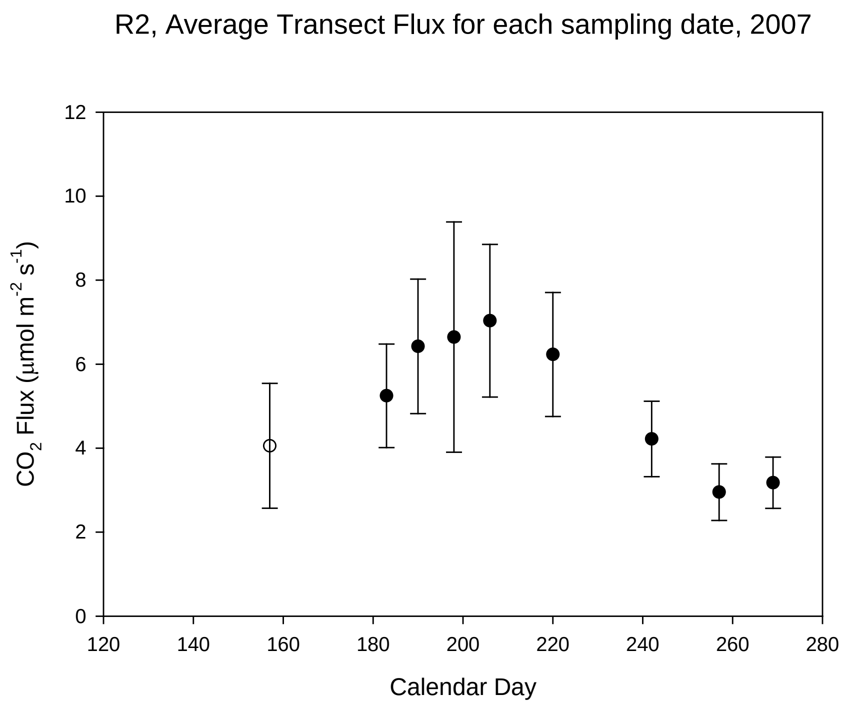


Figure 6. Seasonal pattern of average soil-surface CO_2 flux from transect R2 on the Rannells Prairie in 2006 and 2007. Data (mean ± 1 S.E.) were averaged over all 13 sampling locations on the transect.

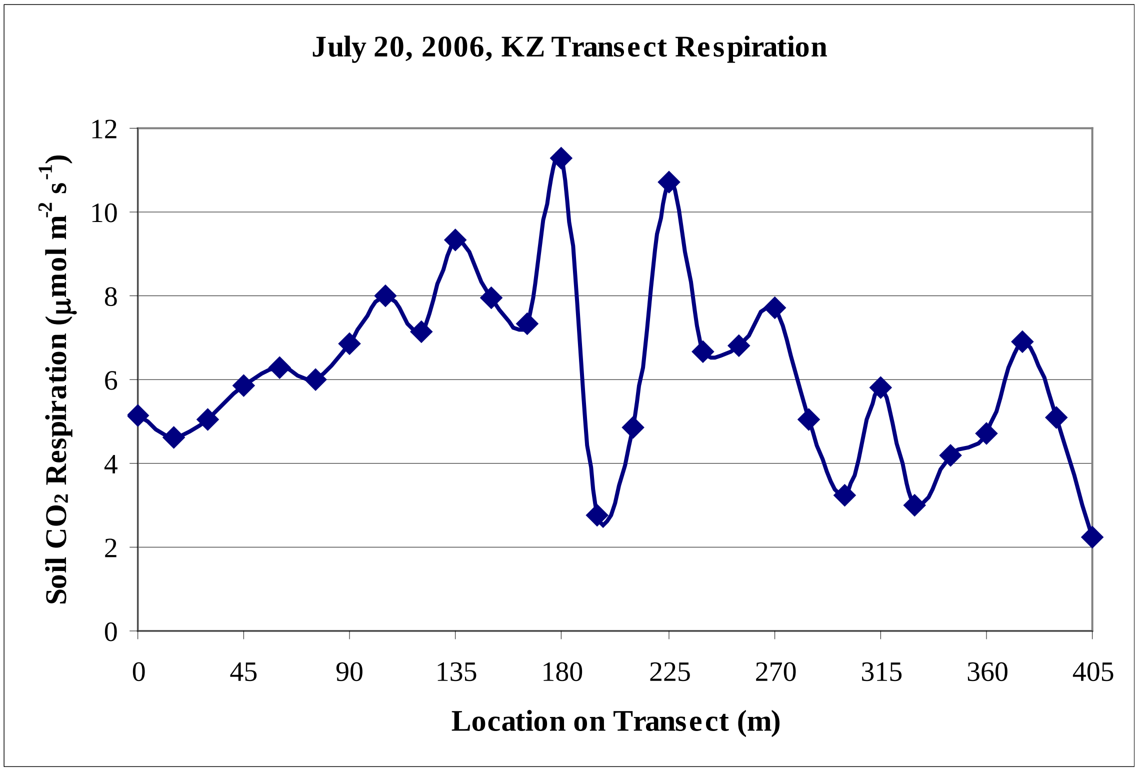


Figure 7. Soil respiration at the 28 sampling locations along the 405-m transect at KZ for July 20, 2006.

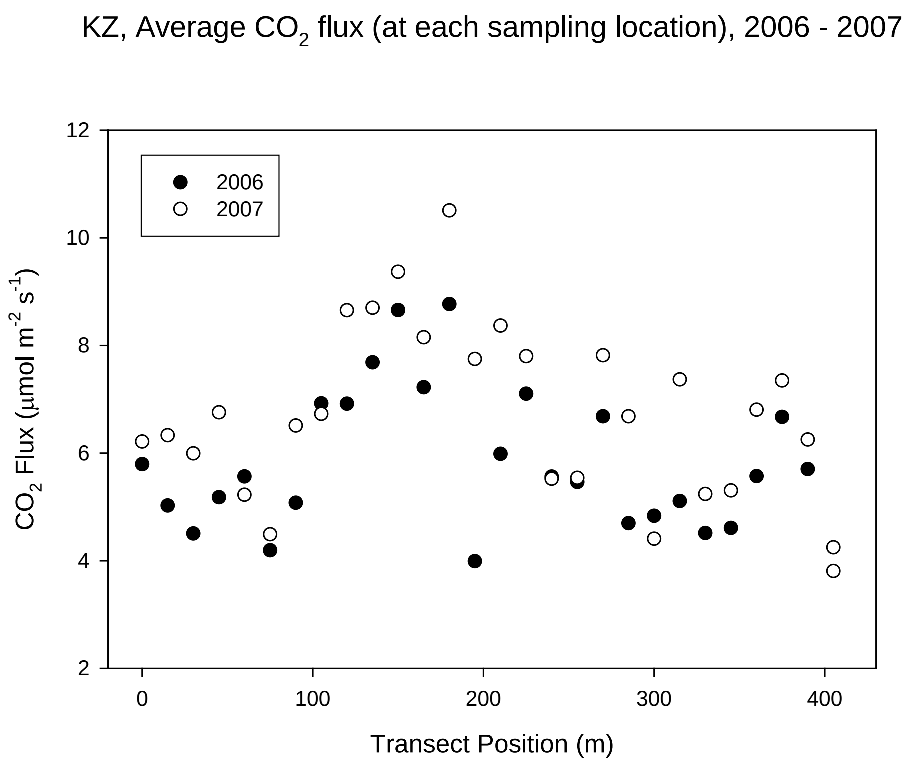
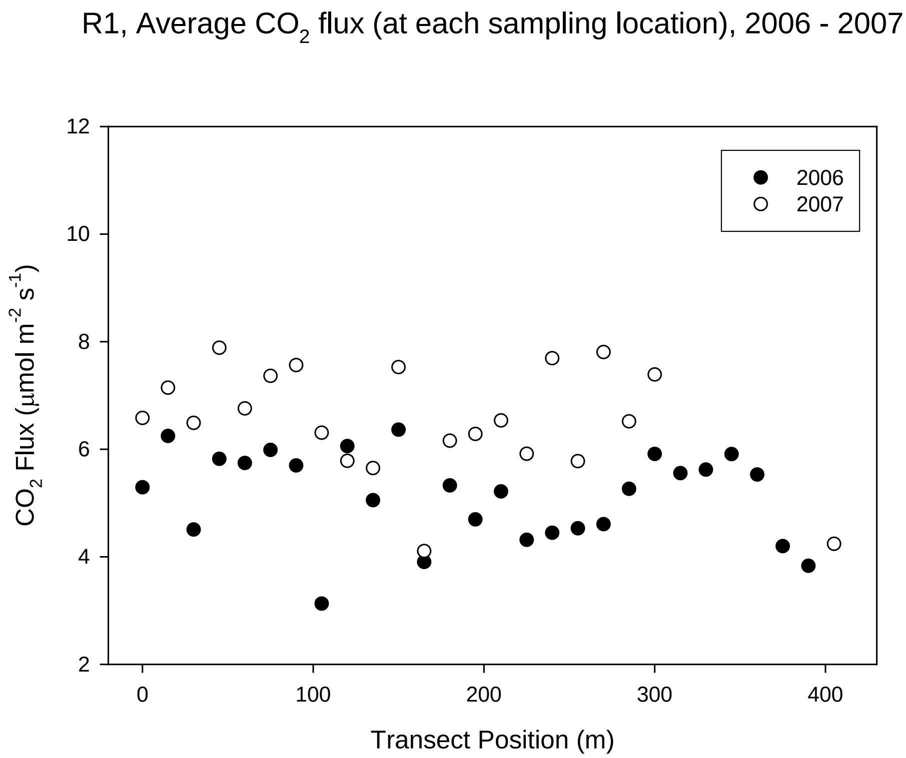


Figure 7. Season-long average CO_2 flux by sampling location on the Konza Prairie transect.



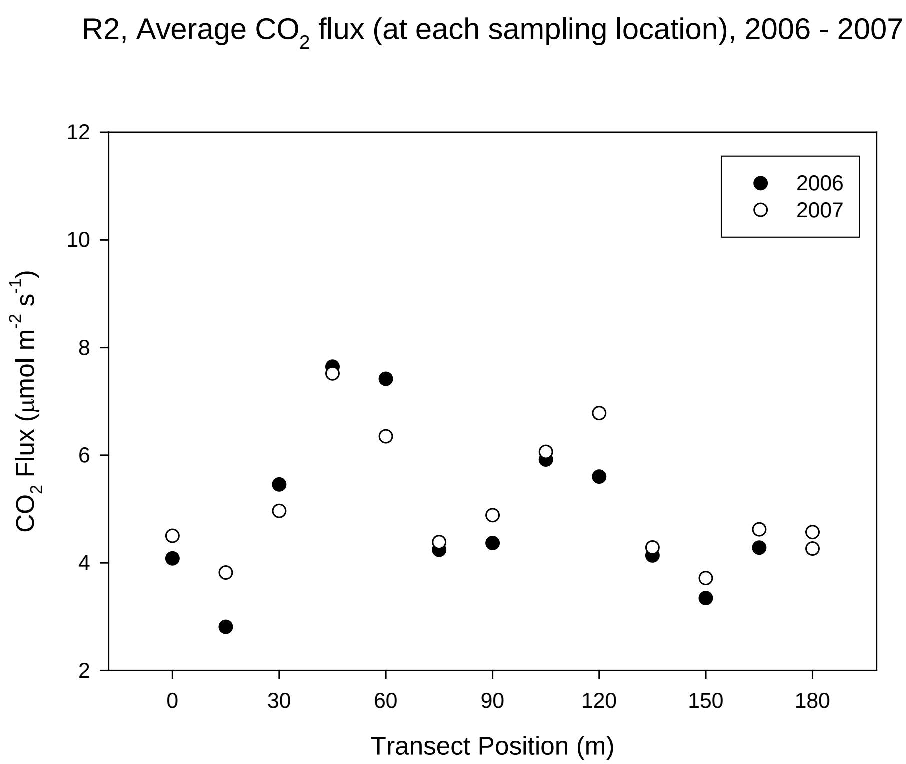


Figure 8. Season-long average CO_2 flux by sampling location on the Rannells R1 and R2 transects.

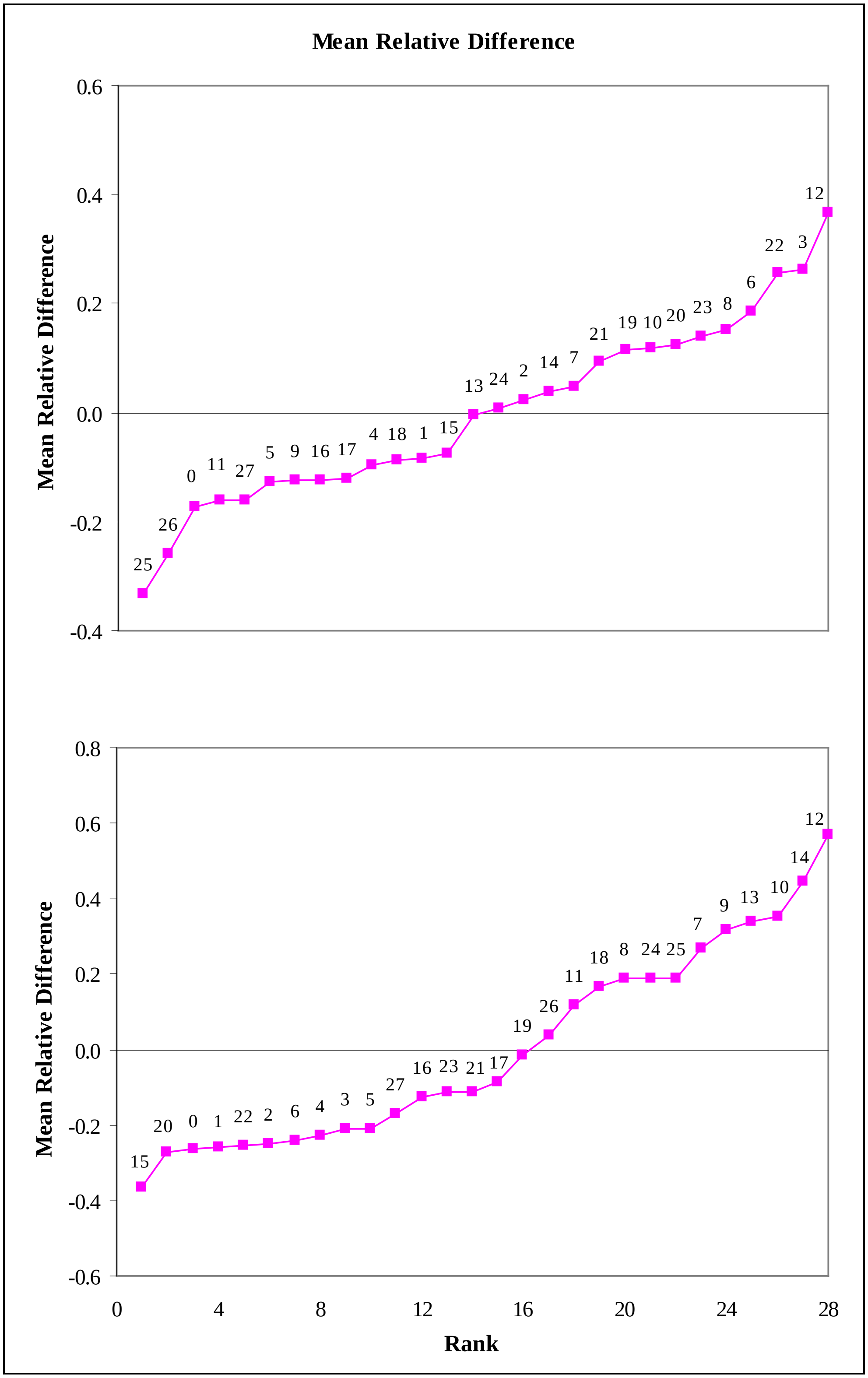


Figure 9. Example mean relative difference and relative difference plots of soil respirations for the (a) Rannells and (b) Konza transects on May 24-25, 2006. The numbers above each symbol represent the label for the sampling collars along a 405-m long transect.

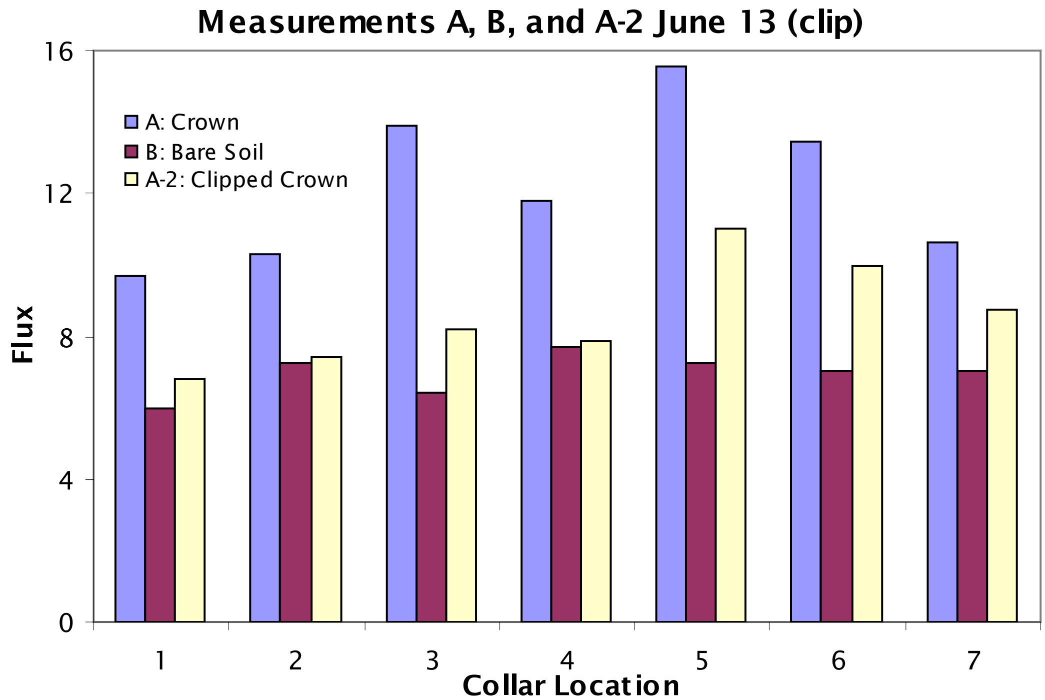


Figure 10. Respiration (μmol m^{-2} s^{-1}) from collars encompassing (A) grass crowns and vegetation and (B) adjacent bare soil. Also shown is a second reading from the A collars after the vegetation had been clipped. On average, canopy respiration (A minus A2) was 3.6 mmol m^{-2} s^{-1}. The difference in soil surface respiration between the zone around the plant crown and the adjacent bare soil (A2 minus B) was 1.6 mmol m^{-2} s^{-1}, a difference of 17 %.

Final Report – October 15, 2007
Midwestern Regional Center of the Department of Energy's National Institute for Climatic Change Research

Improving and Evaluating Dynamic Models of Natural and Managed Ecosystems over the Central and Southern U.S. Using AmeriFlux and MODIS Data

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1. Abstract. While complex terrestrial ecosystem models are increasingly relied upon for integrated assessments, they still remain largely unproven, particularly in their capacity to characterize plant phenology, ecosystem structure, agroecosystems, and coupled carbon and water exchange. Our overall NICCR project objectives were to (1) perform rigorous model validation for an advanced version of the Integrated Biosphere Simulator (or Agro-IBIS, an example of a dynamic biosphere model now including representation of agroecosystems) at the individual site level using AmeriFlux and FACE observational data, and to validate the model across the larger Great Plains, Midwest, and South Central regions using satellite observations and products (e.g., leaf area index, net primary production, and fraction of absorbed photosynthetic active radiation) from the MODIS instrument. The secondary objective was to improve associated process formulations and model parameterizations to bring simulated results into better agreement with observations. While the model performed very well when compared against many observations, several improvements were needed to improve the model's representation of plant phenology, soil moisture stress and elevated CO_2 on plant photosynthesis, and the impact of crop residue on heat, energy, and water exchange between the soil surface and atmosphere in agroecosystems. In the context of climate change, we suggest that revisions to dynamic vegetation models should focus on refinement of simplistic phenology schemes, improving formulations of ecosystem respiration, and representing the effects of litter and residue on energy partitioning at the soil interface.

2. Research activities.

Our funded project targeted a main thrust of the DOE's Research Program ("*Development and testing of ecosystem models needed for integrated assessments"*) by improving and assessing the overall capabilities of a Dynamic Global Vegetation Model (DGVM), called Agro-IBIS (an enhanced version of the Integrated Biosphere Simulator that includes representation of agricultural systems and their management), when applied to the key natural and managed ecosystems found in the eastern two-thirds of the U.S. We specifically assessed the level of accuracy that we could expect to achieve with models that represent coupled carbon-water-energy fluxes between the biosphere and atmosphere, and their response to environmental changes associated with energy production. Our work was addressed in three stages, using a variety of observational data for model improvement, calibration, and validation. The three specific objectives and associated activities were as follows.

(1) **Agro-IBIS model refinement and improvement**. We used meta-analyses, AmeriFlux and FACE site data to evaluate representation of plant phenology and the response of Agro-IBIS leaf and canopy photosynthesis to ambient and elevated atmospheric CO_2. We concluded (a) Agro-IBIS leaf-level photosynthesis was overly responsive to elevated CO_2; the problem was subsequently corrected, and the model was re-calibrated using field data; (b) Plant physiology and overall plant productivity was minimally responsive to extreme soil moisture stress – which was adjusted by using a new formulation of the soil moisture stress function based on field data; (c) Plant phenology was inadequately represented by the model at deciduous forest sites, leading to unsatisfactory representations of species distributions in the upper and lower canopies (e.g., simulation of long-term vegetation dynamics). Adjustments were made to the algorithms for leaf out and senescence of vegetation to more closely match field and satellite

observations. Using AmeriFlux data from agricultural sites, it was concluded that an overall model bias of warmer soil temperatures, higher soil heat flux, and lower soil moisture in agroecosystems managed with *no-tillage* suggested the lack of an explicitly simulated *plant residue layer* at the soil surface led to simulated error in surface energy partitioning. We subsequently made adjustments to the soil layer structure, surface albedo, and thermal properties (e.g., heat capacity) to more adequately represent the impacts of surface residue in agricultural systems to the overall exchange of heat, water, and energy between the soil surface and atmosphere.

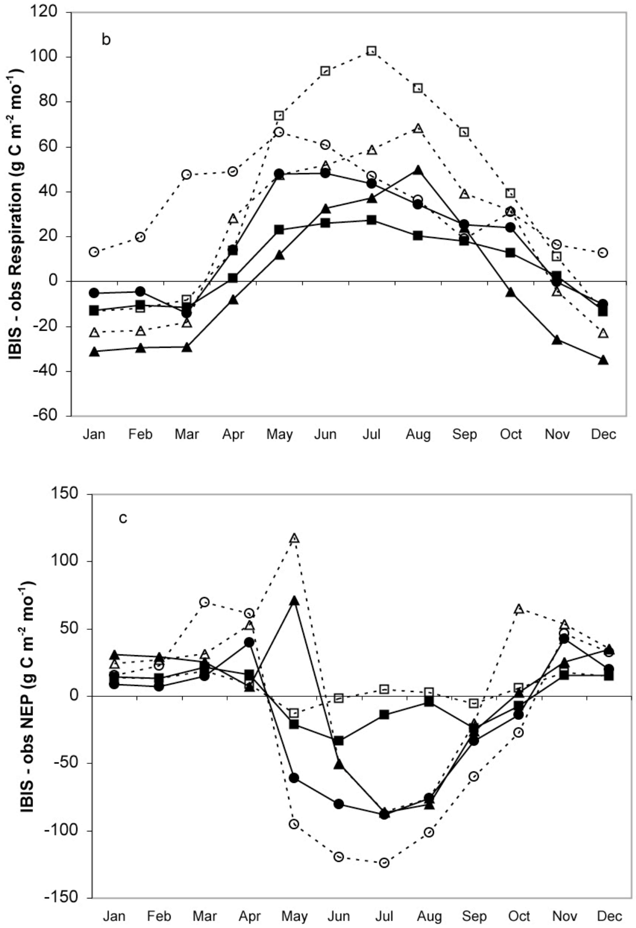

Figure 1. Simulated errors in ecosystem respiration and net ecosystem production (NEP) for Agro-IBIS simulations at three midlatitude AmeriFlux forest sites. Solid lines denote results for fixed vegetation, and dashed lines are for dynamic vegetation runs.

(2) **Agro-IBIS model evaluation for coupled carbon, water, and energy exchange using AmeriFlux data and other field study sites that include a wide range of managed and natural vegetation types and climate regimes** (e.g., crop sites in Mead, NE and Bondvillle, IL; forest sites at Walker Branch TN, Niwot Ridge CO, and Harvard Forest MA). We compared carbon, water, and energy exchange simulated by Agro-IBIS to measurements made using eddy covariance techniques at the Mead, NE AmeriFlux site (corn-soybean, irrigated and rainfed management), and the Bondville, IL AmeriFlux site (corn/soybean rotation). We also utilized many other biometric measurements (e.g., biomass in leaf, stem, root, and grain; leaf area index) for model validation. We also utilized eddy covariance observations of daily, seasonal, and inter-annual carbon dioxide and water vapor exchange between the atmosphere and three mid-latitude forest stands. Measurements of LAI, soil moisture, soil temperature, runoff, soil carbon, and soil surface CO_2 effluxes were also compared with model output.

(3) **Agro-IBIS model evaluation across the regional-to-continental scale using MODIS leaf area index (LAI), net primary production (NPP), and fraction of absorbed photosynthetic active radiation (fPAR) products**. We tested the ability of our model to adequately simulate varied phenology, fPAR, and NPP between cropping systems and grasslands/forests, along with simulations of yield and approximate crop planting and harvest dates for the major crops grown throughout the central and southern U.S. (e.g., wheat, sorghum, corn, and soybean). Monthly-average values of AVHRR NDVI, LAI, and fPAR for the period of 1982-2000 and comparative values collected in 2000-2002 by MODIS were compared to simulated values from the Agro-IBIS ecosystem model to evaluate the magnitude and phenology of vegetation greenness in the United States. Greenness variables were compared over major biomes including conifer and deciduous forest, grassland, shrubland, and cropland.

3. Research highlights.

In our first publication (El Maayar et al., 2006), we first reviewed the effect of elevated CO_2 on photosynthesis of C_3 plants, which illustrated that short-term observations are likely to considerably underestimate the number of plant species that exhibit a photosynthetic downregulation. Several recent long-term field observations have shown that such downregulation starts to be effective only after several seasons/years of plant exposure to elevated CO_2. Second, the Agro-IBIS model was used to illustrate that neglecting the photosynthetic downregulation may significantly bias predictions of net primary production of the middle and high latitudes under high atmospheric CO_2 concentrations (El Maayar et al., 2006). Based on both review of field observations and results of simulations, we concluded that a more appropriate representation of plant physiology and choice of plant functional types may be required in ecosystem models in order to accurately simulate plant responses to changing environmental conditions.

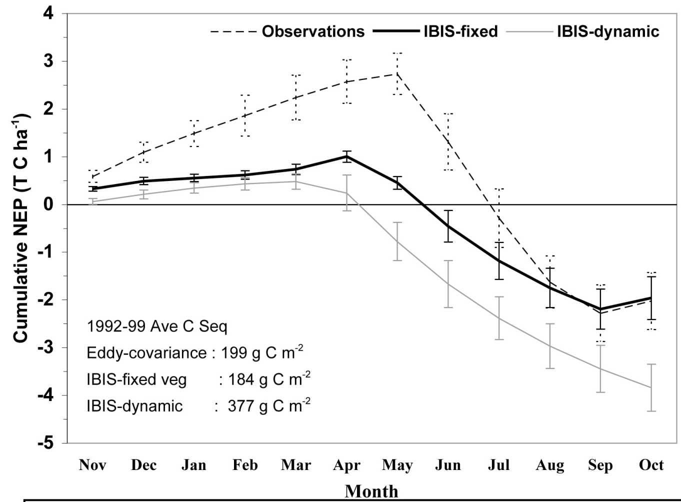

Fig. 2. Accumulated monthly NEP at the Harvard Forest AmeriFlux site (1992-1999 average) compared with IBIS simulations using fixed and dynamic vegetation.

In our exercise of testing of Agro-IBIS against AmeriFlux data at three midlatitude forests (Harvard Forest, Walker Branch, and Niwot Ridge) (Kucharik et al., 2006, Ecological Modelling) an experimental approach was designed to help attribute model errors to the vegetation dynamics and phenology schemes versus other simulated processes such as soil biogeochemistry, plant physiology, and ecosystem respiration. The global to continental scale phenology sub-models poorly represented the timing of budburst and evolution of canopy LAI at deciduous forest sites. Biases of early season green-up of 6 weeks and delayed senescence were noted. Simulated soil temperatures were overestimated during the summer on average by 2-5º C, and underestimated by a similar magnitude during the winter. Ecosystem respiration was overestimated during the growing season, on average, by 20 – 60 g C m^{-2} mo^{-1}, and underestimated during the winter by 10 – 20 g C m^{-2} mo^{-1} across all sites (**refer to Figure 1**). Simulated soil respiration did not capture observed mid-summer peak rates and was generally lower than observed in winter. The overall comparison of simulated net ecosystem production (NEP) to observations showed a significant underestimate of growing season NEP of 25 – 100 g C m^{-2} mo^{-1}, and an overall positive bias of 10 – 40 g C m^{-2} mo^{-1} during the winter (**refer to Figure 1**). It was apparent that the excellent agreement between annual average NEP observations and IBIS simulations in "fixed vegetation" mode resulted from offsetting seasonal model biases. The magnitude of simulated variation in seasonal and inter-annual carbon exchange was generally dampened with respect to observations (**Fig. 2**). The parameterization, and in some cases the formulations (particularly of ecosystem respiration and phenology) of this global scale biosphere model, are limiting its capacity to capture the dynamics of changing water and carbon exchange rates at individual sites. Model parameterizations and formulations were originally constrained and

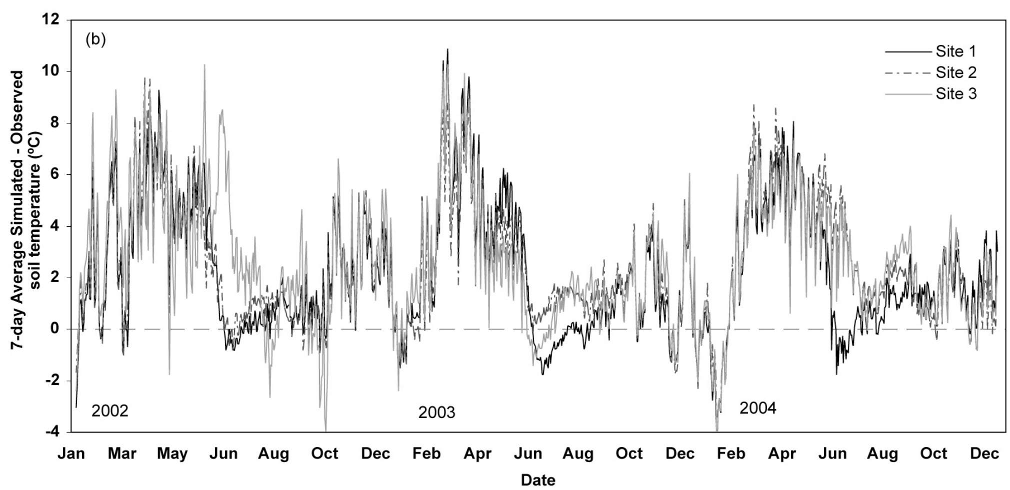

Figure 3. Agro-IBIS simulated errors of daily 10 cm soil temperature at the three agricultural management systems at the Mead, NE AmeriFlux site for 2002-2004.

generalized for application to a wide range of global climate and soil conditions and biome types, likely contributing to model biases. This problem applies to other DGVM's and similar types of biosphere models, and will likely become increasingly relevant as investigators begin to apply their models at higher spatial resolution Kucharik et al., 2006).

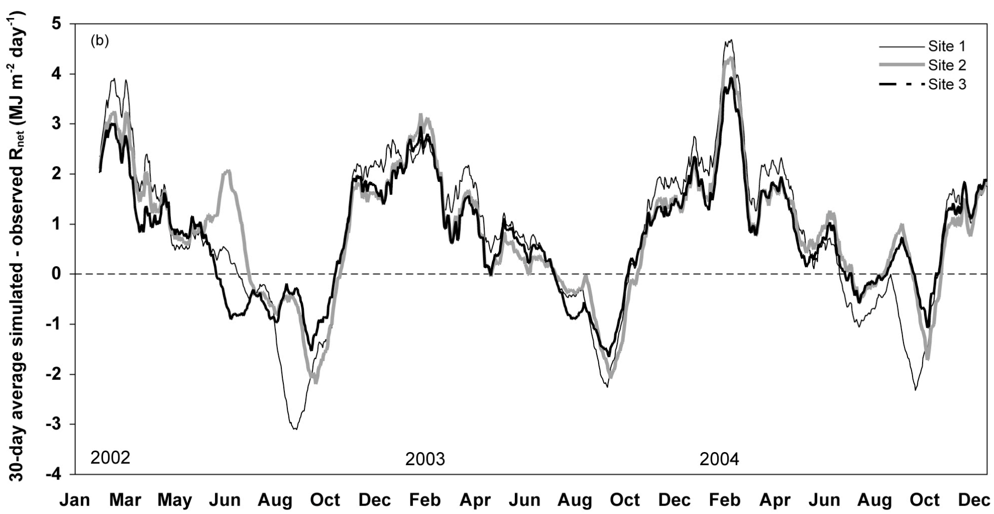

Figure 4. Agro-IBIS simulated errors of daily net radiation at the three agricultural management systems at the Mead, NE AmeriFlux site for 2002-2004.

The Agro-IBIS agroecosystem model was also tested against three years of biometric data, soil temperature and moisture data, and eddy covariance measurements at the Mead, Nebraska AmeriFlux site (Kucharik and Twine, 2007). Three cropping systems managed with no-tillage were studied: (a) irrigated continuous maize, (b) irrigated maize-soybean rotation, and (c) rainfed maize-soybean rotation. The model satisfactorily represented crop growth, carbon (C) allocation, and phenology, as simulated biomass pools were generally within 10% of observations. However, daily net ecosystem production (NEP) was overestimated during the mid-summer by 1-4 g C m^{-2} day^{-1}, and these systematic errors were attributed to underestimates (50-60%) of nighttime ecosystem respiration (R_e). In contrast, the model produced consistent overestimates of R_e during the dormant season by 1-3 g C m^{-2} day^{-1}, which led to a reduced seasonal cycle of R_e.

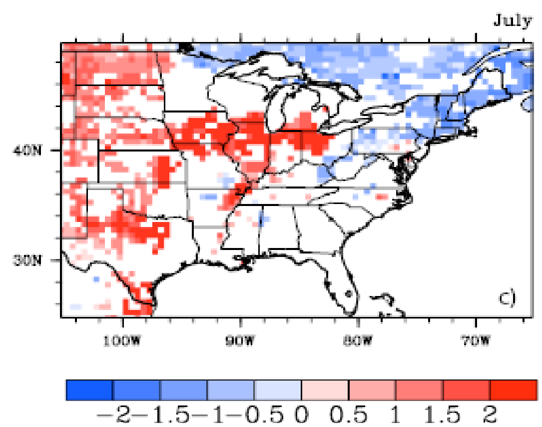

Figure 5. Difference (Agro-IBIS – MODIS) in LAI for July (2000-02 average). Differences shown are statistically significant at p = 0.10.

A majority of these inaccuracies were attributed to simplistic representations of heterotrophic and plant tissue respiration and their empirical dependence on temperature and soil moisture. Soil temperatures were overestimated by 4 – 10ºC in late winter through early summer and then again in late fall, coinciding with the period when vegetative cover was non-existent (**refer to Figure 3**). Annual total net radiation was overestimated by 10%, and total, sensible, and latent heat fluxes were overestimated from winter to early summer by 1-7 MJ m^{-2} day^{-1} (**refer to Figure 4**). Failing to account for the impacts of a crop residue layer on surface albedo and other physical properties is believed to have contributed to these inadequacies in simulated surface energy balance. We concluded that if modelers tune crop-biosphere models to agricultural FLUXNET data without accounting for the impacts of surface residue management, inconsistent estimates of large-scale C and water exchange with the atmosphere may result. This is extremely relevant to studies of the biogeophysical feedbacks to regional climate attributed to land management changes using coupled crop-climate models. Given the increasing adoption of conservation tillage, modelers should focus on including some representation of crop residue dynamics and aim to improve representation of leaf senescence and ecosystem respiration (Kucharik and Twine, 2007).

Agro-IBIS was further evaluated with vegetation greenness information from the AVHRR (1982-2000) and MODIS (2000-2002) sensors (Twine and Kucharik, submitted). Leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (fPAR) products were used to evaluate the model's ability to represent LAI/fPAR magnitude and the onset and offset of growing seasons for crop, forest, grass, and shrub ecosystems of the central and eastern United States. Compared with MODIS, Agro-IBIS showed a mean bias in monthly-averaged LAI of 0.41 with a mean absolute percent difference (MAPD) of 8% in crops, a mean bias of –0.92 (MAPD of –46%) in forests, a mean bias of 0.31 (MAPD of 22%) in grasses, and a mean bias of 0.11 (MAPD of 60%) in shrubs. During the growing season the bias increased in crops (to MAPD of 44%) but decreased in forests (to MAPD of -13%). Despite the apparent overestimation by Agro-IBIS relative to MODIS of peak crop LAI across the Corn Belt region (Figure 5), comparisons with point measurements of LAI suggest that Agro-IBIS may perform better in crop ecosystems than what was found in the MODIS comparison. We conclude that crop modelers should be aware of a potential underestimation of crop LAI in MODIS products, at least within the United States. Similar bias patterns in FPAR occurred in all biomes. Results from this evaluation suggest that (1) the AVHRR record may be used to test a model's simulated growing season length, but not LAI magnitude, and (2) the MODIS products are useful in testing a model's simulated growing season length and LAI/fPAR magnitude at a regional scale but more point measurements, continuing validation of MODIS products, and Agro-IBIS improvements are needed to reduce uncertainty in simulated phenology.

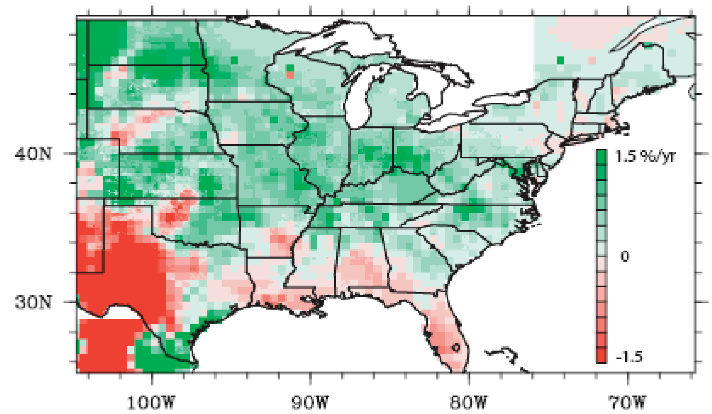

Figure 6. Trend in annual NPP simulated by Agro-IBIS for 1982-2000 (in percent change per year).

Results of an Agro-IBIS simulation (1982-2000) show an increasing trend in annual NPP throughout most of the study domain (Figure 6). Because simulated management practices such as fertilization and hybrid choice were held constant, and irrigation was not simulated, these results suggest a positive trend in production of natural and managed ecosystems that occurs solely from climate trends. The magnitude and spatial pattern of these trends (positive and negative) are consistent with other studies that estimated NPP trend from MODIS GPP products. We conclude that Agro-IBIS is able to simulate ecosystem response to year-to-year variability in climate with magnitude consistent with observation-based studies. This is an important finding as we continue our studies of the impacts of climate change on ecosystem functioning, and improve the simulation of NEP in natural and managed ecosystems.

4. Research products. A global version of the IBIS model continues to be made available at the SAGE website to outside investigators who wish to check previous published results:
http://www.sage.wisc.edu/download/IBIS/ibis.html

5. Publications.

El Maayar, M., N. Ramankutty, and C.J. Kucharik (2006). Modeling global and regional net primary production under elevated atmospheric CO_2: On a potential source of uncertainty. *Earth Interactions* 10, 1-20.

Kucharik, C.J., C. Barford, M. El Maayar, S.C. Wofsy, R.K. Monson, D.D. Baldocchi (2006a). A multiyear evaluation of a dynamic global vegetation model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO_2 and H_2O vapor exchange. *Ecological Modelling* 196, 1-31.

Kucharik, C.J., N.J. Fayram, and K.N. Cahill (2006b). A paired study of prairie carbon stocks, fluxes, and phenology: comparing the world's oldest prairie restoration with an adjacent remnant. *Global Change Biology* 12, 122-139. doi:10.1111/j.1365-2468.2005.01053.x.

Kucharik, C.J. (2006). A multidecadal trend of earlier corn planting in the central U.S. *Agron. J.* 98,1544-1550.

Urbanski, S., C. Barford, S. Wofsy, C. Kucharik, E. Pyle, J. Budney, K. McKain, D. Fitzjarrald, M. Czikowsky, and J. W. Munger. Factors Controlling CO_2 Exchange on time scales from hourly to decadal at Harvard Forest, *Journal of Geophysical Research 112, G02020, doi:10.1029/2006JG000293.*

Kucharik, C.J. and T.E. Twine, 2007. Residue, respiration, and residuals: Evaluation of a dynamic agroecosystem model using eddy flux measurements and biometric data, Agricultural and Forest Meteorology, 146: 134-158, doi:10.1016/j.agrformet. 2007.05.011.

Kucharik, C.J., accepted pending minor revisions. Contribution of planting date trends to increased maize yields in the Central USA, *Agronomy Journal, 2007*.

Twine, T.E., and C.J. Kucharik. Evaluating a terrestrial ecosystem model with satellite information of greenness. Submitted to *Journal of Geophysical Research-Biogeosciences*, Fall, 2007.

6. Student degrees supported (as appropriate).

N/A

DOE National Institute for Climatic Change (NICCR)

Final Report: Michigan Tech Agreement No. DE-FC02-06ER64158
University of Nebraska Subagreement No. 050516Z4

Project title: Evaluation of ecosystem models for beef cattle production

Investigators:
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Abstract: Models were developed to assess effects of climate on grass growth and beef cattle production parameters. Predicted output from the grass growth model (GRASP) was found to be comparable to field observations at three fertility levels. The GRASP model was also utilized to assess effects of climate change on grass growth. In animal studies, thermal indices were developed to predict animal stress based on ambient temperature, relative humidity, windspeed, and solar radiation. Minimum daily temperature (MNTP) and the temperature-humidity index (THI) were the environmental variables having the strongest association to pregnancy rate. The negative association of MNTP and THI are most evident early in the period (0 to 21 day) with a −3.79 and −2.06% change in pregnancy rate for each unit change in MNTP and THI, respectively. Additional equations were developed to depict body temperature profiles of cattle exposed to varying climate conditions.

Research Activities and Highlights:

Grasslands account for approximately 50% of the land area in the Great Plains and the Midwestern states. In the U.S. it supports nearly 100 million beef cows and calves as well as abundant wildlife. The major hypothesis for this project is that an increase in climatic temperatures and related changes in precipitation distribution will change the current grassland pattern and affect the feed resources for beef cows and calves, and ultimately influence overall beef cow reproductive efficiency and confined cattle output. The primary objectives of this study were to assess impact of climatic conditions and related climate changes on quality and quantity of nutrients available from grass for animal production and assess interaction of nutrient supply and environmental factors on beef cattle production in the region.

- Improve forage production models and modeling capabilities to address deficiencies in current animal production models and assess effects of changing climatic conditions on forage output.

The grass model (GRASP) chosen for this study is based on the concepts of a grass production model designed for Australia. The satisfactory performance of this model in tropical and mid-latitude environments suggests that it is capable of simulating grass growth in a wide range of climate and landscape. Thus GRASP (Figure 1) was developed as a mechanistic model simulating the aspects of grass production with predicted soil water profiles, plant growth, and animal parameters. The model uses daily precipitation, temperature, solar radiation, potential evapo-transpiration, and vapor pressure to calculate water balance (runoff, infiltration, evaporation, transpiration, and drainage), pasture growth (green growth, death, and detachment), and various animal indicators (diet selection, utilization and live weight gain). Soil data requirements in the model are soil depth, soil water holding capacity, and wilting point. Modifications were made in the model to account for Central US hydrological cycles, soil nutrient profiles, and environmental characteristics. The model was used to simulate the growth of smooth brome, a cool season grass that is planted through most of North America and shown to be cold and drought tolerant. The simulated grass growth has a good agreement with the field observations for 3 nitrogen fertilizer treatments (Figure 2). The simulated accumulation of grass biomass shows the familiar sigmoidal response, although some slight differences between the simulated and observed grass growth are also noted.

To assess possible climate change effects and their impact on grass growth, the outputs from four general circulation (GC) models were used: Canadian Centre for Climate Modeling and Analysis (CCCM2), Australian model from Commonwealth Scientific and Research Organization (CSIRO2), the Parallel Climate Model (PCM) from National Center of Atmospheric Research, and the Hadley Centre Coupled Model (HadCM3). The GRASP model was used to assess the possible climate change on the grass yield to 2080. From the simulations, the air temperature was projected to increase by about 2-8ºC. Precipitation was projected to increase in spring by all GC models, but decrease or remain unchanged in June and July. The grass yields are projected to increase in spring for all GC models with the largest projected increase approaching 30%, mainly because the increase in temperature and precipitation in spring created favorable conditions for grass growth. The projected grass yields in summer are diverse with two GC models projecting decreasing yield and two GC models projecting weak increasing yield. The GRASP model offers a valuable tool to evaluate climate effects on regional grassland production and an assessment for potential changes in animal production.

- Improve the National Research Council animal production models by developing algorithms from multi-year studies, which better define the effect of climate on cattle reproduction and maintenance energy requirements.

In cow-calf production systems, reproductive performance is essential to the success and profitability of a program. Heat stress plays an important role in reproduction performance. Most cattle in cow-calf production systems are being bred during the early summer months when heat stress events can occur and affect conception rates. Over the 10-yr test period, average beef cow (n ~150 cows /year) pregnancy rates were 54.2, 75.8, and 83.0% through the 21-day, 42-day and 60-day breeding periods, respectively. Average temperature, minimum daily temperature (MNTP), and the temperature-humidity index (THI) were the environmental variables having the strongest association to pregnancy rate, with MNTP accounting for a larger portion of the variation in pregnancy rate for the first 21 days of the breeding season than average temperature and THI. A negative association ($P \leq 0.001$) was found between pregnancy rate and temperature, and between pregnancy rate and THI for the first 21-day and 42-day periods of the breeding season. When evaluated over the 60-day breeding season period, there was only a tendency ($P < 0.10$) for these associations to be negative. The negative association of MNTP and THI are most evident early in the period (0 to 21 day) with a −3.79 and −2.06% change in pregnancy rate for each unit change in MNTP and THI, respectively. In other studies, algorithms were developed to determine the change in net energy requirement for maintenance (NEM) for cattle managed in pens with muddy surfaces. Compiled data found the % increase in NEM is equal to .08*x + .1624* x*x with x equal to mud depth in inches. Additionally, thermal indices were developed to predict animal stress based on ambient temperature, relative humidity, windspeed, and solar radiation.

- Define physiological indicators of climatic stress in cattle, measure responses to climatic stress in cattle, and determine seasonal influences on physiological parameters.

In studies in which yearling cattle that were fed in outside confined areas, body temperature profiles were found to depend on whether cattle are black- or white-hided and differed considerably among season. These data suggest that in the winter, cattle attempt to keep body temperature elevated and fairly constant. Whereas, in the summer, the climatic heat load results in body temperature being elevated in the afternoon, then at night the animal attempts to drive body temperature down or below average, in an effort to prepare for the next day’s heat load. In total, these findings provide useful criteria for utilizing existing thermal indices and physiological measures to quantify effects of climatic stress on cattle. Under both hot and cold conditions, changes in physiological characteristics constitute a change in energy requirement for maintenance.

In reproducing female beef cattle, heat stress is known to alter the follicular development. It is important to understand what mechanisms are at work in the animal to cope and adapt with heat stress and allow them to maintain reproductive performance. Summer trials using non-pregnant crossbred cows were conducted to determine changes in internal body temperature during heat stress periods. To monitor internal body temperature in each trial, a modified data-logging device with a resolution of 0.25°C was used and inserted into the vaginal cavity of each animal. Based on these data, a Fourier series model was developed for predicting body temperature based on maximum daily ambient temperature. Figures 3, 4, and 5 depict the average body temperature of a cow on days when the maximum ambient temperature reached 21.2, 26.7, or 32.2 ºC. When cows experienced a 21.1 ºC day, there appeared to be little variation in body temperature, and body temperature was similar to the expected ~38.6 ºC. When beef cows were subjected to environmental temperatures of 26.7 ºC or 32.2 ºC, there was a greater deviation from normal body temperature (Figure 4 and 5). Cows took on a heat load during the day, and when environmental conditions were conducive, the heat load was dissipated during the evening hours. Body temperatures approached 39.4 ºC when environmental temperatures were 32.2 ºC.

In addition to body temperature, cows were monitored daily for estrus activity and panting scores were taken in afternoon. The preliminary data suggests cows appeared to exhibit a rise in body temperature during estrus, but not consistently across all cows. However, good correlation was found between vaginal and tympanic temperatures.

Research products:

Models: Grass growth simulation model.

Prediction equations:

Adjustment to the temperature-humidity index (THI) for windspeed (WSPD, m/s) and solar radiation (RAD, W/m^2), where THI = = [0.8 × temperature] + [(% relative humidity ÷ 100) × (temperature - 14.4)] + 46.4.

$$\text{Adjusted THI (hourly)} = 4.51 + \text{THI} - (1.992 \times \text{WSPD}) + 0.0068 \times \text{RAD})$$

$$\text{Adjusted THI (daily)} = 6.80 + \text{THI} - (3.075 \times \text{WSPD}) + (0.0114 \times \text{RAD})$$

Pregnancy rate (PR, %) prediction equations using minimum daily temperature and THI.

Fourier series body temperature prediction equation with periodicities of 4, 5, 6, 7, 8, 9, 10, and 12 h.

Students:

Full name	Degree sought	University	Home town	State	% time on project	NIGEC funds received	Date received degree
Rodrigo Arias	M.S.	Univ of NE	Lincoln	NE	25	$5,000	Dec., 2006
Thesis title:	Environmental factors affecting daily water intake on cattle finished in feedlots						
Darci McGee	M.S.	Univ of NE	Wayne	NE	50	$7,500	Aug., 2007
Thesis title:	Effects of summer climatic conditions on body temperature in beef cows						
Melissa Melvin	M.S.	Univ of NE	Lincoln	NE	100	$14,400	

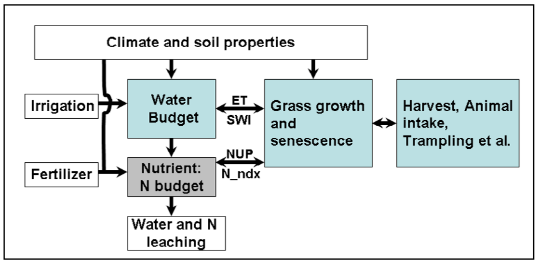

Figure 1. Flow chart of the GRASP model emphasizing the nitrogen (N) module.

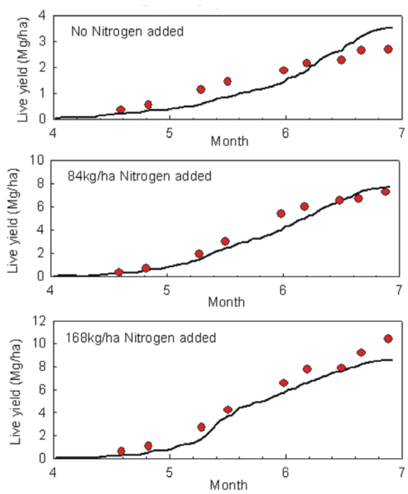

Figure 2. Simulated (line) and observed (dots) smooth brome biomass.

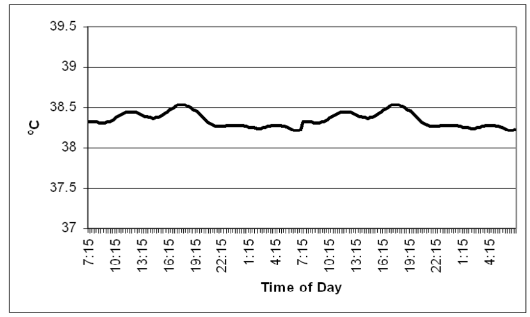

Figure 3. Cow body temperature (ºC) over a 48-hour period when maximum ambient temperature reached 21.1ºC.

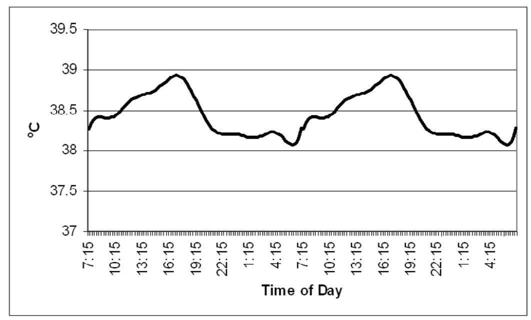

Figure 4. Cow body temperature (ºC) over a 48-hour period when maximum ambient temperature reached 26.7ºC.

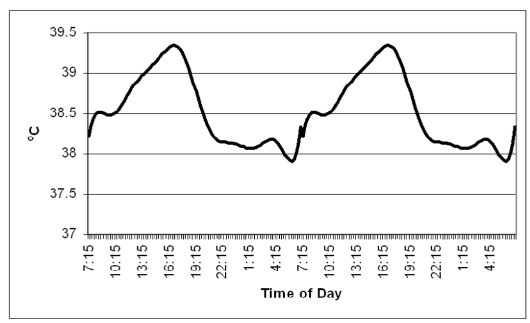

Figure 5. Cow body temperature (ºC) over a 48-hour period when maximum ambient temperature reached 32.2ºC.

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Final Report
Forest-Atmosphere Exchange of CO_2 over a Mixed Hardwood Ecosystem in the Midwest

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1. Abstract

During the project period we continued to conduct long-term (multi-year) measurements, analysis, and modeling of energy and mass exchange in and over a deciduous forest in the Midwestern United States, to enhance the understanding of soil-vegetation-atmosphere exchange of carbon. At the end of the budget period, results from eight years of measurements (1998 - 2006) of above canopy CO_2 and energy fluxes at the AmeriFlux site in the Morgan-Monroe State Forest, Indiana, USA (see Figures 1, 2), were available on the Fluxnet database, and the hourly CO_2 fluxes for 2006 are presented here. The annual sequestration of atmospheric carbon by the forest is determined to be between 240 and 420 g C m^{-2} a^{-1} for the first nine years. These estimates are based on eddy covariance measurements above the forest, with a gap-filling scheme based on soil temperature and photosynthetically active radiation. Data gaps result from missing data or measurements that were rejected in quality control (e.g., during calm nights). While the analysis of annual net ecosystem production has been completed for the budget period of the present project, the observation program and many elements of the associated research on forest-atmosphere exchange processes and a strategy to scale up to a large region are being continued and expanded on a follow-up project. During the project period we also completed a study on the random uncertainty associated with eddy-covariance measurements.

2. Research activities

Objectives:

Long term objectives are to

- determine the current dynamics of carbon cycling for a deciduous forest ecosystem in the Midwest by a concerted measurement effort with various approaches;
- develop, evaluate and assess methods to scale-up from point measurements of fluxes to regional budgets;
- quantify the *regional* contribution to, and impact on, *global* carbon dioxide*;*
- expand and enhance theoretical understanding of the mechanisms, rates and magnitudes of carbon dioxide exchange processes in deciduous forests;
- create links with, and provide integral support to, other carbon cycle related projects being conducted in the region.

Specific objectives for the period August 2006 - September 2007 were to:

- Complete the analysis of the eight full year of observations and present the results in the form of publications and presentations.
- Collect the first part of the dataset for the ninth year (2007).
- Study the interannual variations of the forest carbon exchange dynamics.
- Continue the development of archiving techniques, quality control and data analysis procedures for analysis of the continuous data

Approach:

The principal approach is to measure concentrations and fluxes of carbon dioxide (CO_2) and water/latent heat (H_2O/LE), sensible heat (H) and momentum (τ) directly, using eddy covariance equipment mounted at multiple levels on a 46 m fixed tower in the Morgan-Monroe State Forest in Martinsville, Indiana (Figure 1). These observations are complemented by measurements of the radiation components and photosynthetically active radiation (PAR), soil heat flux, soil temperature and soil moisture, bole temperature and by standard meteorological measurements (precipitation, profiles of temperature and relative humidity, etc.). Currently, the full suite of eddy-covariance and radiation measurements is carried out at two levels above the canopy (at 1.8 and 1.3 times the canopy height) and at one level in the understory, at 2 m above ground. The rationale to maintain two levels of flux measurements above the canopy rests on the notion that they are separated far enough to result in different flux footprints. This approach thus facilitates estimates of spatial representativeness of fluxes within the naturally occurring inhomogeneity of the deciduous forest ecosystem. Details about instrumentation, data acquisition and analysis are given in Schmid et al. (2000).

An integral part of our research approach is our collaboration with our Forest Ecology partner project (led by J.C. Randolph, Indiana University), and with other AmeriFlux sites in the upper Midwest (particularly the UMBS~Flux site, PI: Peter Curtis, Ohio State University). These links serve as a source for comparison of net ecosystem exchange estimates by independent inventory methods (Ecology), and with a different site using very similar methods (UMBS~Flux).

3. Research highlights

Our work addresses unresolved issues around annual NEE estimates and the closure of energy balance from several angles. Much of this is work in progress, and has revealed more new questions than final answers. But such is the nature of this research and reflects its current status.

Measurements at MMSF~Flux have been ongoing since March 1998. Annotated data summaries (1998 – 2006) are available through the Fluxnet database (http://www.daac.ornl.gov/FLUXNET), and 2007 flux data are currently collected and begin analyzed. Our site and instrumentation are presented in Schmid et al. (2000), and an update to our methods of analysis, data quality control strategy and gap-filling (similar to UMBS~Flux) can be found in Schmid et al. (2003). Highlights of our research results (both published and in progress) include:

NEE and Energy Flux Measurements; Annual NEP Estimates

- The annual sequestration of atmospheric carbon by the mixed deciduous forest is determined to be between 240 and 420 g C m^{-2} a^{-1} for the eight years (1998 - 2006) (Figure 2). These estimates are based on eddy-covariance measurements above the forest, with a correction scheme to fill data gaps and replace unreliable values during calm nights ($u_* < 0.3$ m s^{-1}). These results are found to be highly dependent on criteria of data rejection, gap-filling and on the complete coverage of auxiliary data (T_s and PPFD). To put the 1998 data on a calendar-year basis, the fluxes for January and February are estimates based on those from 1999.

  References: Schmid et al. 2000, 2003.

- Figure 1 shows that the rates of net carbon uptake during the vegetative season are in general similar between individual years. Differences in annual net ecosystem production (NEP) are governed primarily by the average wintertime temperature and the length of the vegetative period, as suggested by Baldocchi et al. (2001). Figure 2 shows a scatter-plot of the measured hourly CO_2 fluxes for 2006. However, weather conditions and length of the vegetative season cannot fully explain differences in NEP (or gross primary productivity, GEP) between years, and other factors need to be taken in consideration, as observed for example during the NEP and GEP anomaly in 2004 (table1 and Figure 1)

  Reference: Schmid et al. 2006

- We developed a methodology to estimate the cumulative effect of random uncertainty on annual estimates of net ecosystem productivity of carbon (NEP). Our results (table 1) indicate that the overall uncertainty of annual NEP is dominated by the contribution of the gap-filling model, even at relatively small gap fractions of 20%. Also, our results show the random uncertainty of eddy-covariance based NEP is small compared to other potential sources of systematic bias, although very little is known about the long-tem cumulative covariate effects of systematic bias in the measured flux.

  Reference: Dragoni et al. 2007

4. Research Products

- Data set (eight years of hourly flux data, 1998-2006 in Fluxnet database)
- Meteorological and site data for the AmeriFlux carbon exchange model evaluation initiative (hourly data provided since January 1, 2000).
- Methodology to assess the random uncertainty on eddy-covariance measurements.
- Publications in scientific journals and conference proceedings.

Table 1 : random uncertainty on annual NEP estimate at the MMSF site

Year	**NEP (gC m^{-2} $year^{-1}$)**	**Random uncertainty (gC m^{-2} $year^{-1}$)**
1999	-367	11.8 (3%()
2000	-267	11.2 (4%)
2001	-304	10.4 (3%_
2002	-366	9.6 (3%)
2003	-274	9.9 (4%)
2004	-418	11.9 (3%)
2005	-386	9.7 (3%)
2006	-360	9.9 (3%)

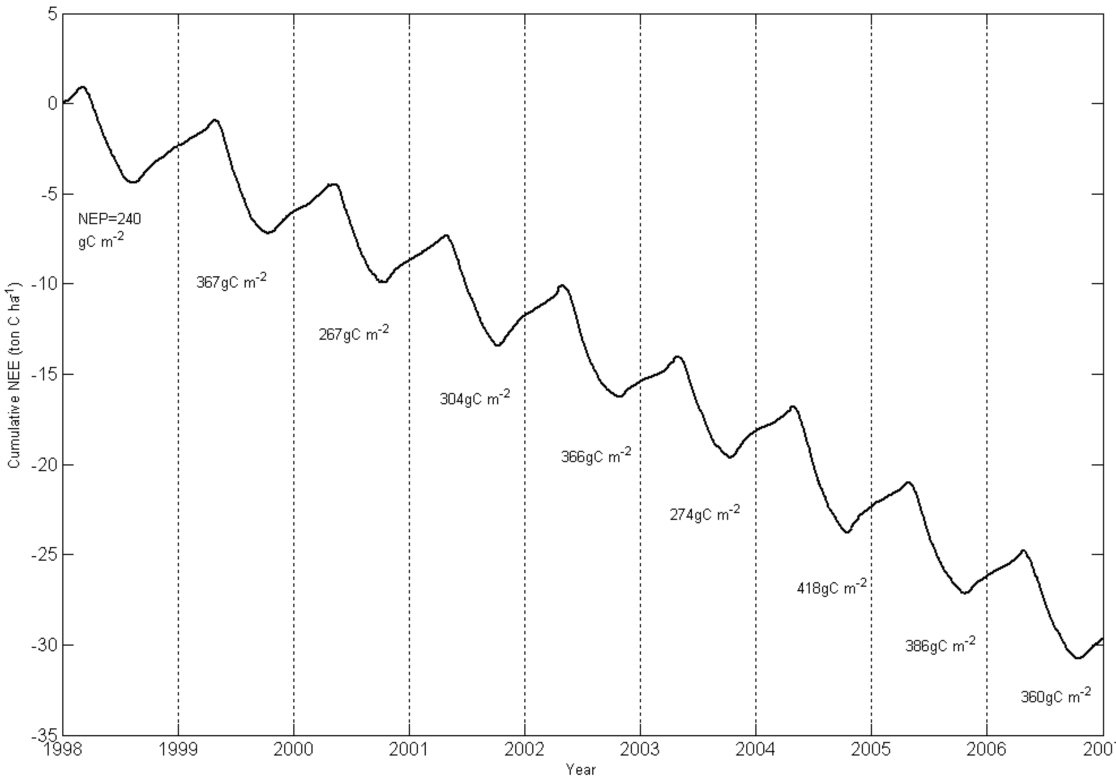

Figure 1: Cumulative NEE over five years at MMSF~Flux. Total 9-year NEP ≈ 30 tons C / ha.

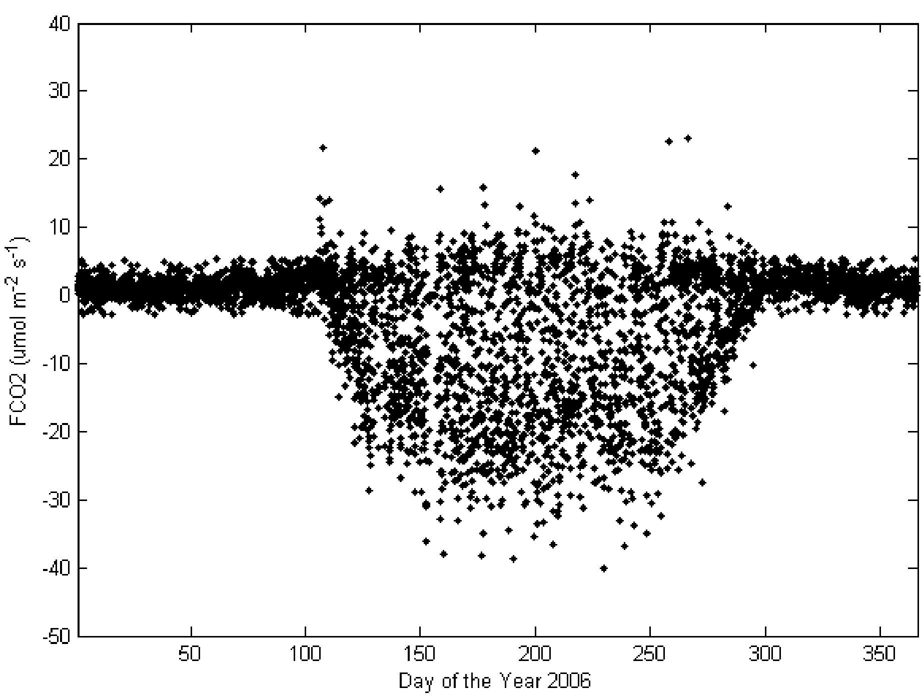

Figure 2: Measured hourly values of CO_2 flux at MMSF for the year 2006, determined by eddy-covariance.

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Caylor K.K, D. Dragoni. On the measurement and variability of sap flux in individual trees. Agricultural and Forest Meteorology – in review

Baldocchi, D.D., T.A. Black, P. Curtis, E. Falge, J. Fuentes, A. Granier, L. Gu, A. Knohl, X. Lee, K. Pilegaard, H.P. Schmid, R. Valentini, K. Wilson, S. Wofsy, L. Xu, and S. Yamamoto: 'Predicting the Onset of Photosynthesis of Deciduous Forests with Soild Temperature and Climate Data: A Synthesis of FLUXNET Data'. International Journal of Biometeorology. DOI: 10.1007/s00484-005-0256-4. 2005.

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6. Student degrees supported

Name	Degree	University	Home town	State	Date of Degree
Norma Froelich	Ph.D.	IU	London	Cana da	PhD, expected 2008
Bin Deng	Ph.D.	IU	Nanning Guangx	China	PhD, expected 2008
Robert Gottlieb	BS	Cornell University	Bloomington	IN	n/a
Joshua Tennen	M.S.	IU	Bloomington	IN	n/a
Andrew Shelby	M.S.	IU	Bloomington	IN	n/a
Jenna Halsey	B.S.A.S	IU	Bloomington	IN	2007
Stephen Griffith	M.S.	IU	Bloomington	IN	n/a
Brandon Schmitt	M.S.	IU	Bloomington	IN	n/a