United States Department of Agriculture

Research, Education & Economics

Agricultural Research Service

National Program Staff
December 2007

National Program 204
Global Change
Accomplishment Report
2002 – 2007

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Introduction

Global Change refers to large-scale change in the Earth's biological, geological, hydrological, and atmospheric systems, whether of natural or human origin. Agriculture is both vulnerable to environmental change and is affecting some factors (e.g. greenhouse gas emission) that contribute to these changes. The formation of the Global Change National Program in 1998 was driven by a need to resolve uncertainty concerning the effects of large-scale environmental change, including changes in climate, composition of the atmosphere and increasing UV-B radiation, on agriculture and food security. There was a need to define the extent that agriculture contributes to large-scale environmental change, and to develop technologies for mitigating undesirable impacts of environmental change or accommodating change via adaptation. During 2002, a new cycle of research was initiated to address these issues. During May 2002, a NP 204 Planning Workshop was held in Denver, Colorado to better coordinate the efforts of ARS scientists working on aspects of Global Change. Because of the strong interdisciplinary nature of global change research, workshop participants recognized the need for periodic reviews of the state-of-the-art of global change research of relevance to agriculture. A unique feature of the Global Change National Program is the inclusion of a synthesis and analysis effort.

Short-term environmental changes at regional scales, such as seasonal drought and late freezes, have long been recognized as primary causes of variation in crop yield and livestock productivity. Addressing the likelihood that agricultural and other terrestrial ecosystems will also be affected by long-term global-scale changes, such as human impacts on the Earth's atmosphere and energy balance is now deemed necessary. At the same time, we must investigate the potential for agriculture to play a role in mitigating the factors driving environmental change, for instance by sequestering carbon.

This Accomplishment Report summarizes selected accomplishments that have resulted from the research developed to address the objectives of the 2002 Global Change Research Action Plan. These accomplishments are categorized in this report by the Program's major components:

The success of the Global Change National Program in meeting goals established in its Action Plan will be assessed by a panel of outside experts. An Executive Summary of their assessment report will be published on the ARS website during 2008 and will provide a basis on which to begin planning for the next 5-year research cycle of global change topics. For the next 5-year research cycle the Global Change National Program will be merged with the Air Quality Research Program and the Soil Resource Management Research Program to form the Soil and Air Resource Management National Program.

The immediate and expected impacts of global change have become urgent concerns of citizens from all nations. The ARS Global Change Program's vision is for a productive and profitable future for American agriculture based on a research program that correctly anticipates changes and provides the tools for producers to adapt to them. The research accomplishments reported by this report were conducted to make this vision a reality for the U.S. and the world.

ARS is proud to submit this Accomplishment Report to the Assessment Panel, to our stakeholders and customers, and to the Nation. ARS National Program Staff are confident that the research performed under the Global Change National Program reflects a productive research portfolio given the available resources.

Background

General

The Agricultural Research Service (ARS) is the intramural research agency for the United States Department of Agriculture (USDA), and is one of four agencies of the Research, Education, and Economics USDA mission area. During 1998, ARS organized its research under a National Program structure to better manage and coordinate research efforts. These programs bring coordination, communication, and empowerment to the more than 1200 research projects carried out by ARS. Management of National Programs focuses on enhancing the relevance, quality, and impact of ARS research.

The Global Change National Program (NP) 204 was formed with the mission of developing and providing adaptation, mitigation, and management strategies to the individual farm, ranch, and rural community, and to natural resource decision-makers, to allow them to derive optimal benefit from the positive aspects of global change and deal effectively with the detrimental effects. The Global Change National Program's mission follows the ARS Strategic Plan which, in turn, is directed towards achieving the goals mandated by the USDA Research Education and Extension Mission Strategic Plan and the USDA Strategic Plan.

The boundaries of ARS national programs often overlap when working to solve agricultural problems, and thus many of the projects contributing to NP 204 also contribute to the goals of other programs. Global Change research, which is part of the Natural Resources and Sustainable Agriculture Systems (NRSAS) unit, is linked with other NRSAS programs including Water Availability and Watershed Management (NP 211); Soil Resource Management (NP 202); Air Quality (NP 203); Pasture, Forages, and Rangeland Systems (NP 215); Manure and Byproduct Utilization (NP 206); Integrated Agricultural Systems (NP 207); and Bioenergy and Energy Alternatives (NP 307). Global Change research is also linked with National Programs in the Crop Production and Protection unit, including Plant Genetic Resources, Genomics and Genetic Improvement (NP 301), and Plant Biological and Molecular Processes (NP 302). A significant part of the Global Change research is conducted in collaboration or conjunction with projects in one or more of these other national programs.

The impetus for ARS to conduct research on global change came from the Global Change Research Act of 1990. The purposes of the Global Change Research Act of 1990 are to 'assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change' [Sec. 101(b)] and to 'produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change' [Sec. 104(d)(3)]. The Global Climate Change Prevention Act of 1990 (Title XXIV of the 1990 farm bill) directs the Secretary of Agriculture to 'study the effects of global change on agriculture,' including 'the effects of simultaneous increases in temperature and carbon dioxide on crops of economic importance; the effects of more frequent severe weather events on such crops; the effects of potential changes in hydrologic regimes on current crop yields' and many other specific areas affecting agriculture [Sec. 2403(a)(1)].

ARS works with the U.S. Office of Global Change Research Programs (USGCRP) to coordinate research and share expertise with other agencies working on issues related to global change via the U.S. Climate Change Science Program (CCSP).

Planning, Review, and Implementation

Management of each of the ARS National Programs follows a 5-year program cycle consisting of planning, review, implementation, and assessment. A workshop on the Global Change National Program was held in Denver, Colorado, October 4-7, 1999. Approximately 120 participants attended, representing all groups of customers, stakeholders, and partners with an interest in global change research. They participated in two days of plenary sessions and breakout groups to identify and prioritize key research needs in the area of agriculture and global change. This was followed by a day of discussion by ARS scientists in attendance designed to incorporate the input of the stakeholders into a National Program Action Plan.

Customers and stakeholders interested in global climate change differed from those in other ARS research program areas in that most represented other government agencies, with only a few agricultural producers. Special attention was paid during the preparation of the Global Change National Program Action Plan to ensure that key problem areas identified by the customers and stakeholders were addressed in the plan.

Four principal research components were identified. Writing groups were organized to address each of these components, and each writing group subdivided its component into problem areas based on the stakeholder input. The writing team used input from workshops, their own knowledge of the subject matter area, and input from other ARS scientists to identify problem areas. Each problem area then became the subject of a two-to-three page Problem Statement summarizing current knowledge, gaps, and objectives for use in developing planning documents that will frame ARS research. Relevant ARS research locations were identified for each problem area. The problem statements for each of the components were collated and organized by a writing team leader with iterative editorial suggestions from all contributing writers.

Problems Identified by Customers

The following sections discuss each of the Global Change National Program components. Component issues are stated briefly and the state of knowledge is discussed. ARS locations across the U.S. contributed to research in the Global Change National Program encompassed by this report. ARS scientists have taken advantage of this geographical, disciplinary, and issue-oriented diversity by collaborating across locations.

The ARS Global Change National Program focuses on four aspects of global change, and these aspects form the four components of the Action Plan:

Carbon Cycle and Carbon Storage: The historical loss of soil carbon during the westward expansion and cultivation of the U.S. appears to have stabilized and perhaps even reversed direction. Preliminary ARS research has shown that conversion from conventional tillage to reduced or no-till causes soils to act as repositories for carbon rather than sources of atmospheric carbon dioxide (CO_2). Similarly, recent research suggests that the perennial grasses established on the more than 34 million acres of marginal croplands enrolled in the Conservation Reserve Program have deposited organic carbon (C) in the soil at an annual rate of more than a half ton per acre. Carbon-depleted cultivated soils thus may represent a substantial potential repository for C to help reduce projected increases in atmospheric CO_2. However, management practices that favor C storage may also affect yield or profitability through their interaction with other soil factors, including temperature, water status, and nutrient cycling.

Trace Gases: Much has been learned about the role of agriculture in trace gas production, including ammonia (NH_3), nitrogen oxides (N_2O), nonmethane hydrocarbons, sulfur dioxide, and various organosulfur compounds, however much work remains. Recent research has shown that feed quality and digestibility dramatically affect the amount of methane produced by ruminants. In waste management, research has shown that dry storage of manure results in significantly less methane production than wet storage, yet the use of wet storage is increasing because it is more economical in large, concentrated feeding operations. Research is necessary to eliminate this conflict between environmental and economic goals. It is also known that better use of natural nitrogen (N) sources, such as legumes, and less use of manufactured fertilizers should lead to lower N_2O emissions.

Agricultural Ecosystem Impacts: One certainty among the many uncertainties associated with climate change is a continued increase of atmospheric CO_2 concentration. Some favorable effects of rising CO_2 have implications for crop yields and forage production, especially if precipitation amounts decline. Experimental evidence obtained by growing plants over a range of CO_2 concentrations representative of various times in history suggests that plant growth, yield, and water-use efficiency have increased and will continue to do so as CO_2 levels rise. Such positive responses are especially evident under controlled conditions. However, they have not been studied extensively under field conditions in interaction with other expected changes such as higher temperature, higher ozone concentrations, and higher UV-B radiation levels. Temperature effects on crop growth and yield have also been studied extensively, but primarily in isolation. The effects of climate change on pests, including insects, weeds, and diseases, have been the subject of much speculation and some research. The interactive effects of multiple stressors, both in cropping systems and on grazinglands, will be a primary research topic in this component. As in other components, development and improvement of models and testing them against field data will also receive emphasis to improve confidence in prediction of future impacts of global change on agricultural productivity.

Changes in Weather and the Water Cycle at Farm, Ranch, and Regional Scales: General circulation models (GCMs) used to simulate climate responses to rising greenhouse gas (GHG) concentrations predict that changes in precipitation will accompany rising temperatures. The models show that temperature and precipitation will not change uniformly across the globe but will vary regionally, meaning that some regions may prosper while others suffer. Changes in seasonal patterns of precipitation, such as a shift in the peak rainfall period, also could be important. Overall warming could have deleterious effects on agricultural water supplies in areas such as the Central Valley of California that depend on snowfall as a water source. Some GCMs predict that variability will increase with global warming and this also has the potential to affect agriculture. The frequency and magnitude of large-scale atmospheric forces such as El Nino may be enhanced. Droughts, floods, and periods of excessive heat or cold may occur more frequently, and the frequency and severity of extreme weather events such as storms also may increase. Increases in extremes are viewed with concern because variation in weather, from cool, wet spring planting periods to extended summer droughts, is currently the most significant cause of instability in crop yields. Assessments also indicate that greater variability would increase crop insurance costs and disaster payments.
Each of these topics is also traceable to priorities identified by the CCSP Strategic Plan (http://www.climatescience.gov/Library/stratplan2003/final/default.htm).

Synthesis and Integration of Research Findings

A critical need in global change science and policy is the integration of information on this subject from different sources. The complexity of global change scientific issues creates a need to develop broad insight and conclusions from the scientific literature and databases. The current need by the scientific community, policymakers, and the public for integrated synthesis of information concerning global change justifies particular attention to this as a special activity in the ARS Global Change National Program.

Publication of research in scientific journals alone cannot provide the insight or keep pace with the need for integrated information in the policy arena. New data, analyses, and models must be assembled from many different sources across the research community if scientific direction and policies are to be based on the most current information. New developments are particularly rapid in the global change area. ARS scientists provide input to global change policy decisions, but reliance on journal publication of research is insufficient to contribute in a comprehensive and timely manner. Thus, ARS scientists participating in the Global Change National Program are encouraged to synthesize and integrate information from all sources, including those outside their own activities. ARS scientists will maintain an awareness of needs for policy development and scientific guidance through routine contacts with customers, stakeholders, National Program Staff, governmental and nongovernmental agencies, and the scientific community. ARS scientists and National Program Leaders will identify needs for information about global change that transcend the routine research and publication processes.

How this Report was Constructed and What it Reflects

Information about NP 204 achievements and their impact is organized in this report according to National Program research components and program goals, as described in the Global Change National Program Action Plan. The four NP 204 Research Components are outlined, and followed by selected accomplishments, along with the impact and/or potential of those achievements to solve the problems and meet the needs identified by the customers and stakeholders.

Most of this report is derived from NP 204 scientists who were asked to summarize their project's major accomplishments during the last five years in terms of impact, and provide key references documenting those accomplishments. Consequently this report does not include all accomplishments achieved in the national program but rather, those key accomplishments selected by the National Program Leaders who authored this report. As a result, this report encompasses a subset of the total spectrum of NP 204 accomplishments, chosen to illustrate and exemplify the total progress and achievements at the National Program level. This document reports only selected refereed publications, patents, and grants as supporting documentation and does not include the large number of abstracts and manuscripts presented at workshops, symposia and interagency conferences.

Action Plan Components and Plans to Address Problems

Responding to needs expressed by customers and workshop participants, it was determined that research would focus on the following goals and specific projected outcomes for each research component:

Component I: Carbon and Carbon Cycle

Goal: Provide the data and the process understanding necessary to describe the current and potential roles of agriculture in the global carbon cycle with sufficient accuracy to inform policy and aid producers in making decisions that are both economically and environmentally sound.

Projected Outcomes of Carbon and Carbon Cycle Research: Defined animal and cropping system effects- including tillage and residue management- on soil carbon storage, rates of soil carbon change, and carbon quality in different soils and climatic zones, including analysis of long-term experiments; quantification of inorganic fertilizer and organic byproduct effects on plant growth and soil carbon storage, rates of soil carbon change, and carbon quality in different soils and climatic zones.

Component II: Trace Gases

Goals: Develop cropping, pasture and rangeland systems that manage N to minimize trace gas emissions while preserving productivity; address the need for synthesis of information to provide larger scale estimates of agricultural emissions, which is currently difficult because of the lack of appropriate models and a shortage of data necessary to develop and test them at the appropriate spatial scales.

Projected Outcomes of Trace Gas Research: Agricultural sources of emissions will be identified and quantified. Effective mitigation strategies for reducing trace gas emissions will be developed, leading to reduced impact of agriculture on climate. Conservation tillage and other energy-efficient farming methods will reduce net fuel consumption; fertilizer use efficiency will be increased by reducing erosion losses, leaching, and volatilization; animal manures and waste disposal will be reduced by increasing animal feed conversion efficiency.

Component III: Agricultural Ecosystems Impacts
Goals: Determine how projected global change and management practices/patterns will affect the ecology, hydrology, productivity, and sustainability of agricultural ecosystems, and develop successful strategies and practices to adapt to change and improve productivity.

Projected Outcomes of Agricultural Ecosystems Research: Predictions will be possible as to which agricultural systems will most respond to global change, including regions that may be susceptible to deleterious responses. Verifiable, physiologically based criteria will be determined to assess and predict losses of economic yield induced by weeds, arthropod pests, and diseases associated with climate change. Improved crop management systems will be developed that minimize economic and environmental uncertainties while maximizing the positive aspects of global change in agriculture.

Component IV: Changes in Weather and the Weather Cycle at Farm, Ranch, and Regional Scales
Goals: Modify and use weather generation models to examine the effects of increased weather variability on agriculture, hydrologic cycles and natural environments under varying carbon dioxide, climate, and management scenarios. Downscale results so that the impact of General Circulation Models (GCMs) on local water supplies can be examined, and develop methods to represent local scale heterogeneity in larger scale models to improve predictive capability.

Projected Outcomes of Changes in Weather and the Weather Cycle at Farm, Ranch, and Regional Scales Research: Technologies will be developed to estimate hydrologic and agricultural parameters from remotely sensed data. Methods to monitor water and energy fluxes at large scales will be more reliable; environmentally stressed areas will be more detectable. Water management strategies will be more responsive to the effects of global change. Management and policy decisions by water supply districts, farmers, other resource managers, and policymakers on issues relating to water and energy balances at various scales will be more informed. Improved data, models, and decision support systems will be developed to assess the effects of global change on vegetation response, environmental response, and economic returns. Management strategies will be developed to ameliorate the impacts of global change on agricultural and natural lands.

Component I: Carbon Cycle and Carbon Storage

Topic: Cropping System and Tillage

Goal: Define animal and cropping system effects, including tillage and residue management, on soil carbon (C) storage, rates of soil C change, and C quality in different soils and climatic zones; include analysis of long-term experiments.

Projected Impact: Improved cropping and tillage systems that supply high quality food and fiber while reducing agriculture's impact on the environment through reduced greenhouse gas emissions and enhanced soil C storage.

Summary: Soil conservation practices such as decreasing tillage intensity (volume of disturbance), increasing surface residue retention, and crop diversity were associated with increased soil organic carbon (SOC) and improved soil quality. Manure may mitigate greenhouse gas (GHG) emission by contributing to C sequestration, provided that it is managed to avoid run-off and its plant nutrient availability is quantified and managed. Elevated atmospheric CO_2 was associated with increased plant biomass production, which, if linked with conservation tillage, has the potential to increase soil carbon. The impact of elevated CO_2 on plant C:N ratio was species-, cultivar-, and plant age-dependent. Advances were realized in understanding how long and under what conditions SOC sequestration occurs. Conservation practices that increase SOC also improve soil water infiltration and nutrient cycling, and decrease erosion risks, thus helping protect water resources while improving soil productivity and enhancing profitability. The research directly addressed questions about production management effects on C sequestration needed for development of C credit trading, such as the carbon credit program developed for the National Farmers Union (NFU) in collaboration with the Chicago Climate exchange, and conservation programs focused on simultaneously reducing GHG emissions and improving soil productivity.

Selected Accomplishments

- **Soil C sequestration and mitigating greenhouse gas (GHG) emissions from agriculture: Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet)**. A nationwide network of ARS researchers is quantifying agricultural contributions to GHG emissions, storage of C in soils, and how conservation practices mitigate GHG emission. The questions posed by GRACEnet are designed to provide data and management guidelines for producers wishing to participate in C credit trading. The management approaches to achieve greater soil organic matter SOM storage were found to be somewhat dependent upon climatic region, however, growing crops with little soil disturbance and raising animals on pasture were determined to be two key management variables for increasing soil C storage. Synthesis publications outlined region-specific management strategies for North American, and the economic and social benefits of management to enhance C sequestration. Information from a recent GRACEnet review articles ((Special North American GRACEnet Issue)) was used in the development of a carbon credit program for the National Farmers Union (NFU) in collaboration with the Chicago Climate Exchange. Initially in North Dakota, producers participating in the program, which included continuous conservation tillage (no-till) and seeded grassland are credited with 0.4 MT CO_2/acre/yr for no-till and 0.75 MT CO_2/acre/yr for seeded grass over the duration of a five year contract; about 830,000 acres were enrolled during the 2006 sign-up period. The NFU program has expanded to include 25 states in the U.S. with a total enrollment (2006 and 2007) of 2.54 million acres. In addition, a carbon credit program for native rangeland was started in 2007 by the NFU. These carbon credit programs have the potential to realize multiple benefits for agricultural producers, including increased farm income and improvements in soil quality, while concurrently mitigating agriculture's impact on global climate change.

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Franzluebbers, A.J.*, R.F. Follett, J. M. F. Johnson, M.A. Liebig, E.G. Gregorich, T.B. Parkin, J.L. Smith, S.J. Del Grosso, M.D. Jawson, and D.A. Martens. 2006. Agricultural exhaust: A reason to invest in soil. *Journal of Soil and Water Conservation* 61(3):98A-101A.

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Jawson, M.D., S.R. Shafer, A.J. Franzluebbers, T.B. Parkin, and R.F. Follett. 2005. GRACEnet: Greenhouse gas Reduction through Agricultural Carbon Enhancement network. In A.J. Franzluebbers and R.F. Follett (eds.) Greenhouse gas contributions and mitigation potential in agricultural regions of North America. *Soil and Tillage Research* 83:167-172. (Special North American GRACEnet Issue)

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Martens, D.A., W. Emmerich, J.E.T. McLain, and T.N. Johnsen. 2005. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. *Soil and Tillage Research* 83:95-119. (Special North American GRACEnet Issue)

- **Infrastructure for assessment of CO_2 exchange in Midwest corn/soybean systems.** Eddy covariance flux stations were established in corn /soybean fields under chisel plow management to measure net ecosystem exchange, and automated chambers were installed to provide hourly estimates of soil respiration. Carbon assimilation and efflux measured by these continuous monitoring systems were supplemented by below- and above-ground biomass measurements of net primary production to develop C balance estimates. Additional plant canopy and soil characterizations were completed to refine understanding of the interaction between energy and water transfer with CO_2 exchange. Results indicate that the standard corn/soybean production system is in near-C-equilibrium with annual and seasonal trends strongly influenced by soil water and temperature.

Prueger, J. H., J. L. Hatfield, T. B. Parkin, W. P. Kustas, and T. C. Kaspar. 2004. Carbon dioxide dynamics during a growing season in Midwestern cropping systems. *Env. Manage*. 33:S330-S343.

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Ochsner, T. E., T. J. Sauer, and R. Horton. 2007. Soil heat storage measurements in energy balance studies. *Agron. J.* 99:311-319.

Sauer, T. J., J. W. Singer, J. H. Prueger, T. M. DeSutter, and J. L. Hatfield. 2007. Radiation balance and evaporation partitioning in a narrow-row soybean canopy. *Agric. For. Meteorol*. 145:206-214.

- **Agricultural management strategies for enhancing C storage.** The influence of agricultural practices on SOC and movement of water-soluble silica (Si) were evaluated in a long-term wheat-fallow experiment established during 1940. Sweep tillage (minimum disturbance) retained 14% more SOC than moldboard plow (inversion tillage). The SOC has a protective effect by suppressing Si solubility. Adoption of a conservation tillage system increases C storage and provides a mechanism for impeding siliceous pan formation, thus enhancing drainage of these soils. The results provide a basis for guidance of best management practices for publicly funded conservation programs or market-driven C credits.

Gollany, H.T., R.R. Allmaras, S.M. Copeland, S.L. Albrecht, and C.L. Douglas Jr. 2005. Tillage and Nitrogen Fertilizer Influence on Carbon and Soluble Silica Relations in a Pacific Northwest Mollisol. *Soil Sci. Soc. Am. J*. 69:1102-1109.

- **Synthesis of C sequestration and crop biomass management research**. Integrated agriculture strategies are needed to reduce impacts on the global climate via methods such as C sequestration and other conservation, and to lead to improved soil and environmental quality. Analysis of stover yield, SOC, and $\delta^{13}C$ data showed that corn harvest alternatives and residue management practices have implications for source C incorporation into corn-derived SOC. They may offer guidance when determining rates of stover harvest for energy purposes while maintaining soil production potential. A detailed review of the literature led to an estimate of the minimum amount of crop biomass needed to be returned to the soil to prevent loss of SOC. This information will impact crop residue harvest guidelines, which are crucial to developing a sustainable biomass energy industry.

Grant: A Comprehensive Demonstration of a Community-Scale Biomass Energy System (PI - Lowell Rasmussen; University of Minnesota,– USDA-Rural Development Agency. Subcontract to USDA-ARS-NCSCRL subaward ($103,604) (3/30/06-3/29/09).

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Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: A literature review. *Agronomy Journal*. 96:1-17.

Wilts, A.R., D.C. Reicosky, R.R. Allmaras, and C.E. Clapp. 2004. Long-term corn residue effects: Harvest alternatives, soil carbon turnover, and root-derived carbon. *Soil Science Society of America Journal* 68:1342-1351.

- **Residue decomposition of soybean varieties grown under free-air CO_2 enrichment (FACE).** The effect of enhanced atmospheric CO_2 on aboveground residue of eight soybean varieties was investigated using a field study with two CO_2 levels-- 370 ppm (ambient) and 550 ppm (free-air CO_2 enrichment, FACE). Across varieties, overall residue N concentration was increased by FACE, with a slight increase of residue C concentration. Total mineralized C was somewhat increased by FACE and total mineralized N was increased by FACE, suggesting that increased N_2-fixation affected decomposition. Across CO_2 levels, varietal differences were observed, with the oldest variety having the lowest residue N concentration and the highest C:N ratio. Mineralized N was lowest in the oldest variety, illustrating the influence of high C:N ratio. The breeding selection process may have resulted in some varietal differences in residue quality which can result in increased N or C mineralization under elevated CO_2. This suggests that variety may impact soil C storage potential in soybean production systems and should be incorporated into C management strategies for agriculture.

Prior, S.A., H.A. Torbert, G.B. Runion, H.H. Rogers, D.R. Ort, and R. L. Nelson. 2006. Free-Air Carbon Dioxide Enrichment of Soybean: Influence of Crop Variety on Residue Decomposition. *Journal of Environmental Quality* 35:1470-1477.

- **Tillage impacts on soil CO_2 flux characterized**. Soil CO_2 flux is affected by tillage implement (e.g. chisel vs. moldboard plow), tillage depth, tillage volumes, time of tillage (spring vs. fall), and tillage interactions with wind speed and SOC level. The loss of CO_2 from soil can be proportional to the volume of soil disturbed, which is consistent with the observed losses of SOC. However, the time of tillage or the soil conditions at the time of tillage modify this loss. These results illustrate the value of maintaining soil cover to minimize soil erosion and that timing of tillage and tillage intensity can be modified to reduce tillage-induced CO_2 flux.

Gesch, R.W., D.C. Reicosky, R.A. Gilbert and D.R. Morris. Influence of tillage and plant residue management on respiration of a Florida Everglades Histosol. 2007. *Soil Tillage Research*. 92:156-166.

Li, Y., Zhang, Q.W., Reicosky, D.C., Bai, L.Y., Lindstrom, M.J., and Li, L. 2006. Using 137cs and 210pbex for quantifying soil organic carbon redistribution affected by intensive tillage on steep slopes. *Soil and Tillage Research.* 86:176-184.

Morris, D.R., Gilbert, R.A., Reicosky, D.C., Gesch, R.W. 2003. Soil organic matter decomposition potentials in organic soils under different tillage methods. *Sugar Journal*. 66(1):22-23.

Morris, D.R., Gilbert, R.A., D.C. Reicosky, and R.W. Gesch. 2004. Oxidation potentials of soil organic matter in Histosols under different tillage methods. *Soil Science Society of America Journal.* 68:817-826.

Prior, S.A., R.L. Raper, and G.B. Runion. 2004. Effect of Implement on Soil CO_2 Efflux: Fall vs. Spring Tillage. *Transactions of the American Society of Agricultural Engineers* 47(2):367-373.

Reicosky, D.C. 2001. Tillage-induced CO_2 Emissions and carbon sequestration: Effect of secondary tillage and compaction. In: Garcia-Torres, L.et al., (eds). Xul, Cordoba, Spain. *Conservation Agriculture, A Worldwide Challenge*. p. 265-274.

Reicosky, D.C. 2002. Tillage and gas exchange. *Encyclopedia of Soil Science*. p. 1333-1335.

Reicosky, D.C., and D.W. Archer. 2007. Moldboard plow tillage depth and short-term carbon dioxide release. *Soil and Tillage Research* 94:109-121.

Reicosky, D.C., Lindstrom, M.J., Schumacher, T.E., Lobb, D.E., Malo, D.D. 2005. Tillage-induced CO_2 losses across an eroded landscape. *Soil and Tillage Research*. 81:183-194.

Reicosky, D.C., Wilts, A.R. 2004. Crop-residue management. In: Hillel, D., (Eds). *Encyclopedia of Soils in the Environment.* Vol. 1. Oxford, UK Elsevier. p. 334-338.

- **Effect of implement on soil CO_2 efflux: Fall vs. spring tillage.** Measurements were taken following a grain sorghum crop on a loamy sand soil to characterize soil CO_2 efflux patterns as affected by tillage implement (disk-type, chisel-type, and undisturbed) and time of tillage (fall and spring). During fall, increased CO_2 efflux was related to degree of soil disturbance. Losses were similar for the chiseled and undisturbed treatments and lower than the disked treatment. With spring tillage, CO_2 losses for the untilled and disked treatment were similar, while the chiseled treatment exhibited a slightly lower loss. Results suggest that selection of fall tillage equipment that maintains surface residue and minimizes soil disturbance could help reduce CO_2 loss. Such considerations for spring tillage operations would not result in a substantial change of CO_2 loss.

Prior, S.A., R.L. Raper, and G.B. Runion. 2004. Effect of Implement on Soil CO_2 Efflux: Fall vs. Spring Tillage. *Transactions of the American Society of Agricultural Engineers* 47(2):367-373.

- **Elevated atmospheric CO_2 effects on soil C storage in conventional and conservation cropping systems.** This work compared the impacts of conventional (tillage) vs. conservation (no-till) management on a silt loam soil with grain sorghum and soybean rotation under elevated atmospheric CO_2. The conservation system also uses three rotated winter cover crops: wheat, crimson clover and sunn hemp. The effect of management and CO_2 concentration (ambient = 365 ppm; elevated = 725 ppm) on biomass over two cropping cycles (4 years) were evaluated. Changes of soil C concentration were observed after two cropping cycles. Elevated CO_2 increased cumulative residue production by 30% regardless of management practice. Conservation practices led to an increased cumulative residue production of 90%. Increases in cumulative inputs resulted in changes in soil C concentration. Both elevated CO_2 and conservation management resulted in increased soil C concentration, particularly in the surface increment (0-5 cm). Elevated CO_2 resulted in a dramatic increase in soil C concentration (44%) compared to ambient CO_2 in the conservation treatment. The effects of CO_2 and management were also significant for other depths. Results suggest that, with conservation management in an elevated CO_2 environment, greater residue amounts increased soil C storage.

Prior, S.A., G.B. Runion, H.A. Torbert, H.H. Rogers, and D.W. Reeves. 2005. Elevated Atmospheric CO_2 Effects on Biomass Production and Soil Carbon in Conventional and Conservation Cropping Systems. *Global Change Biology* 11:657-665.

- **SOC storage quantified in conservation tillage systems for different regions.** Degradation of soil and water resources with cropping can be a perceived and a real problem throughout the world. SOC storage was quantified in conventional and conservation tillage systems with different crop rotations throughout the southeastern US. Tillage system had a dominating influence on SOM and soil microbial properties in the southeastern US and cropping intensity had a dominating influence in Alberta, Canada. Crop and cattle producers are encouraged to utilize conservation tillage management techniques to help retain SOM and build soil quality. Conservation management would benefit taxpayers and nature enthusiasts by avoiding environmental degradation of the landscape. These results are applicable to small- and medium-sized farms throughout the southeastern US.

Arshad, M.A., A.J. Franzluebbers, and R.H. Azooz. 2004. Surface-soil structural properties under grass and cereal production on a Mollic Cryoboralf in Canada. 2004. *Soil and Tillage Research* 77:15-23.

Franzluebbers, A.J., and B.G. Brock. 2006. Surface-soil responses to silage cropping intensity on a Typic Kanhapludult in the piedmont of North Carolina. *Soil and Tillage Research* 93:126-137.

Terra, J.A., D.W. Reeves, J.N. Shaw, and R.L. Raper. 2005. Impacts of landscape attributes on carbon sequestration during the transition from conventional to conservation management practices on a Coastal Plain field. *Journal of Soil and Water Conservation* 60:438-446.

Terra, J.A., J.N. Shaw, D.W. Reeves, R.L. Raper, E. van Santen, and P.L. Mask. 2004. Soil carbon relationships with terrain attributes, electrical conductivity surveys and soil map units in a coastal plain landscape. *Soil Science* 169:819-831.

- **SOM and environmental quality with conservation-management systems**. Summarized reference information was produced for public dissemination to describe the multi-faceted changes of SOC resulting from conservation management, and its consequences on important soil functions, including water infiltration and soil biological activity and diversity. Environmental benefits of conservation management in agriculture are being realized on more than 100 million acres of cropland in the U.S. and there is potential for even greater benefit with further adoption.

Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage Research* 66:195-203.

Franzluebbers, A.J. 2002. Soil biology. In: R. Lal (ed.) *Encyclopedia of Life Support Systems*, UNESCO, New York, http://greenplanet.eolss.net. p. 001-028.

Franzluebbers, A.J. 2002. Ecology and the cycling of carbon and nitrogen. In: R. Lal (ed.) *Encyclopedia of Soil Science*, Marcel Dekker, Inc., New York. p. 374-377.

Franzluebbers, A.J. 2002. Animals and ecosystem functioning. In: R. Lal (ed.) *Encyclopedia of Soil Science*, Marcel Dekker, Inc., New York. p. 68-71.

Franzluebbers, A.J. 2007. Integrated crop–livestock systems in the southeastern USA. *Agronomy Journal* 99:361-372.

Johnson, J.M.F., A.J. Franzluebbers, S. Lachnicht-Weyers, and D.C. Reicosky. 2007. Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution*. 150:107-124

- **Evaluated tillage-erosion and short-term CO_2 loss**. Highly efficient, cost-effective tillage/residue management systems are needed to limit erosion and loss of soil C in agricultural production systems. Tillage-induced CO_2 and soil carbon losses and soil physical properties were measured along transects in a recently cropped wheat field using a portable chamber technique. Moldboard plow tillage caused large, short-term losses of CO_2 relative to chisel plow and no-till; the magnitude of CO_2 loss was smaller on highly eroded plots compared to depositional areas. Assessment of soil translocation in a farmer's field after 30 years of moldboard plowing identified tillage as a cause of erosion and soil C losses. Spatial variation in C loss across a rolling landscape complicates the determination of non-point sources of soil C loss and suggests a need for improved soil conservation tillage methods to maintain soil and air quality in agricultural production systems.

Li, Y., Zhang, Q.W., Reicosky, D.C., Bai, L.Y., Lindstrom, M.J., and Li, L. 2006. Using 137cs and 210pbex for quantifying soil organic carbon redistribution affected by intensive tillage on steep slopes. *Soil and Tillage Research*. 86:176-184.

Reicosky, D.C., Lindstrom, M.J., Schumacher, T.E., Lobb, D.E., Malo, D.D. 2005. Tillage-induced CO_2 losses across an eroded landscape. *Soil and Tillage Research*. 81:183-194.

- **Short-term tillage-induced CO_2 losses can help explain the long-term decline of soil C associated with intensive cropping.** Forms of strip tillage showed that short-term C loss was proportional to the volume of soil disturbed in the tillage operation. This is significant because it suggests that other forms of minimum tillage may be more beneficial for C sequestration. Agronomic crop yields from the strip tillage study continued similarly for strip tillage and conventional tillage with only a slight depression in no till, but with reduced input costs, there was no economic penalty from conservation tillage. A long-term study showed that CO_2 loss was consistently higher for moldboard plow surface than from a surface not tilled, but all fluxes were lower from plots with one year of fallow than with a recent crop. This research has received international recognition resulting in numerous invited presentations.

Reicosky, D.C. 2001. Tillage-induced CO_2 Emissions and carbon sequestration: Effect of secondary tillage and compaction. In: Garcia-Torres, L.et al., (eds). Xul, Cordoba, Spain. *Conservation Agriculture, A Worldwide Challenge*. p. 265-274.

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Reicosky, D.C., and D.W. Archer. 2007. Moldboard plow tillage depth and short-term carbon dioxide release. *Soil and Tillage Research*. 94:109-121.

Reicosky, D.C., Wilts, A.R. 2004. Crop-residue management. In: Hillel, D., (Eds). *Encyclopedia of Soils in the Environment.* Vol. 1. Oxford, UK Elsevier. p. 334-338.

- **Energy co-products with potential to enhance soil properties.** Biomass energy sources can supplement petroleum-based energy, however, removal of excessive amounts of biomass from fields may enhance erosion and decrease SOC. After cellulosic ethanol production, char and a high-lignin co-product remain. Both decompose slowly, have potential to help sequester C, and neither product caused any deleterious effects on crops or soil. The high-lignin fermentation co-product enhanced soil physical and chemical properties. Returning these co-products to the soil may allow the agricultural community to reduce the global rise in CO_2 emission while taking advantage of renewable energy development opportunities.

Grant: Environmental Enhancement through corn stover Utilization (PI Robert Brown) Iowa State University. Awarding agency – USDA-Rural Development. Subcontract to USDA-ARS-NCSCRL subaward ($150,000) (3/30/06-3/29/09).

Grant: Department of Energy Interagency agreement. Implications of using corn stover as a biofuel. Funded FY 2001 ($28,000), 2002 (28,000), 2003 ($24,000).

Day, D., Evans, R.J., Lee, J.W., Reicosky, D.C. 2005. Economical CO_2, SOx and NOx capture from fossil fuel utilization with combined renewable hydrogen production and large scale carbon sequestration. 2005. *Energy*. 30(14):2558-2579.

Johnson, J.M.F., D. Reicosky, B. Sharratt, M. Lindstrom, W. Voorhees, and L. Carpenter-Boggs. 2004. Characterization of soil amended with the by-product of corn stover fermentation. *Soil Science Society of America Journal.* 68:139-147.

Johnson, J.M.F., B.S. Sharratt, D.C. Reicosky, and M.J. Lindstrom. 2007. Impact of high lignin fermentation by-product on soils with contrasting soil organic carbon. *Soil Science Society of America Journal* 71:1151-1159.

Skjemstad, J.O., Reicosky, D.C., Wilts, A.R., Mcgowan, J.A. 2002. Charcoal carbon in U.S. agricultural soils. *Soil Science Society of America Journal* 66:1249-1255.

- **Impacts of intensive tillage and wind speed on decreasing soil CO_2 concentrations, related soil C loss and soil subsidence.** Subsidence of drained Histosols (organic or muck soils) in the Everglades Agricultural area is a concern for the sustainability of crop production in southern Florida. Histosol subsidence is caused by accelerated oxidation of organic matter due to drainage, but little was known about the impact of agricultural practices like tillage. Research was conducted to assess the impact of intensive tillage and wind speed on soil CO_2 concentrations and its relations to soil carbon loss and soil subsidence. This work demonstrated the direct effect of wind speed and intensive tillage on decreasing soil CO_2 concentrations, and helps explain the rapid oxidation of organic soils and subsequent soil loss associated with intensive tillage. Slowing or reversing the subsidence of histosols contributes to mitigation of agriculturally released CO_2, thus reducing impacts of agriculture on climate change.

Gesch, R.W., D.C. Reicosky, R.A. Gilbert and D.R. Morris. 2007. Influence of tillage and plant residue management on respiration of a Florida Everglades Histosol. *Soil Tillage Research*. 92:156-166.

Morris, D.R., Gilbert, R.A., Reicosky, D.C., Gesch, R.W. 2003. Soil organic matter decomposition potentials in organic soils under different tillage methods. *Sugar Journa*l. 66(1):22-23.

Morris, D.R., Gilbert, R.A., D.C. Reicosky, and R.W. Gesch. 2004. Oxidation potentials of soil organic matter in Histosols under different tillage methods. *Soil Science Society of America Journal*. 68:817-826.

- **Assessments of soil C stocks under various land uses.** ARS scientists are now leading an inventory effort for the USDA with an upcoming U.S. Agriculture and Forestry Greenhouse Inventory that is currently under review and projected for 2007 publication. This effort serves a major role in identifying the importance of SOC and the large potential that exists under different land uses to sequester SOC to help mitigate the greenhouse effect. It has greatly broadened the scope of the identification of lands worthy of consideration as carbon sinks. It has provided data for the development of national inventories for various land uses, and information about how long and under what conditions SOC sequestration occurs. These estimates are used by computer modelers, U.S. policy makers in USDA and other State and Federal agencies in addressing the role of currently used and improved practices and possible future policies on C sequestration.

Leavitt, S.W., R.F. Follett, J.M. Kimble, and E.G. Pruessner. 2007. Radiocarbon and $\delta^{13}C$ depth profiles of soil organic carbon in the U.S. Great Plains: A possible spatial record of paleoenvironment and paleovegetation. *Quaternary International* 162-163:21-34.

Conant, R.T., K. Paustian, S.J. Del Grosso, and W.J. Parton. 2005. Nitrogen pools and fluxes in grassland soils sequestering carbon. *Nutrient Cycling in Agroecosystems* 71: 239-248.

Pepper, D.A., S.J. Del Grosso, R.E. McMurtrie, and W.J. Parton. 2005. Simulated carbon sink response of shortgrass steppe, tallgrass prairie and forest ecosystems to rising [CO2], temperature and nitrogen input. *Global Biogeochem. Cycles* 19, GB1004.

Bandaranayake, W., Y.L. Qian, W.J. Parton, D.S. Ojima, and R.F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the century model. *Agronomy Journal*. 95:558-563.

Lal, R., R.R. Follett, and J.M. Kimble. 2003. Achieving soil carbon sequestration in the US: a challenge to the policy makers. 168 (12): 827-845. *Soil Science*.

Eve, M.D., M. Sperow, K. Howerton, K. Paustian and R.F. Follett. 2002. Predicted impact of management changes on soil carbon stocks for each agricultural region of the conterminous United States. *J. Soil and Water Cons*. 2002. v. 57 p. 196-204.

Eve, M.D., K. Paustian, R.F. Follett, and E.T. Elliott. 2000. A national inventory of changes in soil carbon from National Resources Inventory data. pp. 593-610. In R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (eds.). *Assessment Methods for Soil Carbon*. Lewis Publishers, Boca Raton, FL. 696 p.

Topic: Grazinglands, CRP and Buffers

Goals: Quantify the magnitude and rate of change of soil C storage with different land use management practices, in different ecoregions, and under different plant communities; determine the rate and extent of soil C storage on a regional or soil basis, including the potential of restorative management such as CRP and buffer-strip initiatives; identify and quantify secondary benefits of soil C storage; and quantify CO_2 fluxes on a seasonal basis under different ecosystems.

Projected Impact: Enhanced quality of grazinglands, CRP, and buffer strips while attaining maximum potential C storage.

Summary: Moderate levels of grazing were reported to enhance soil C storage in perennial grassland pastures of the southeastern US, while high biomass removal in Pennsylvania pastures resulted in a net of loss of C. Further, N-fertilization of tall fescue pastures in the Southern Piedmont region of the US enhanced soil C storage under plants with high (compared to low) levels of endophyte infection. Chamber and micrometeorological gas flux measurements indicated that vegetative growth stage, soil water content, and temperature were three primary factors determining seasonal variations of grassland CO_2 flux rates. Collectively, the results suggest limited ability of mesic pastures, CRP lands and grassland buffer strips to sequester C within certain limits of forage removal, and that the application of N fertilizer may be required for maximal C gain. Micrometeorological flux measurements in rangelands of the southwestern US suggest that soils with high levels of carbonates may be net sources of C to the atmosphere, and that grasslands are more water-use efficient than shrublands in assimilating atmospheric CO_2.

Selected Accomplishments

- **SOC sequestration under pasture management systems in the Southern Piedmont US**. Typical pasture management systems in the US Southern Piedmont were characterized for long-term SOC storage. Particulate organic C was highly related to total organic C, but became an increasingly larger portion of total organic C near the soil surface The cumulative effects of 20 years of tall fescue management on SOC and N were also determined. Soil under tall fescue with a high percentage of plants infected with the endophyte stored more SOC and N than soil under tall fescue with a low percentage of endophyte infection. This extra C and N in soil due to the presence of the endophyte was in intermediately sized soil aggregates, which are important for reducing water runoff and improving water quality. These results suggest that well-fertilized tall fescue pastures with a high percentage of plants infected with the endophyte have the potential to help offset rising atmospheric CO_2.

Franzluebbers, A.J., and J.A. Stuedemann. 2002. Particulate and non-particulate organic C depth distribution under pasture management in the Southern Piedmont USA. *Environmental Pollution* 116:S53-S62.

Franzluebbers, A.J., and J.A. Stuedemann. 2005. Soil carbon and nitrogen pools in response to tall fescue endophyte infection, fertilization, and cultivar. *Soil Science Society of America Journal* 69:396-403.

- **SOC sequestration and agricultural GHG emissions in the southeastern US**. Available data were assembled on C storage in soil and GHG emissions from agricultural management systems in the southeastern US. Management systems that stored more C in soil included conservation tillage, utilization of cover crops, more complex crop rotations, optimum N fertilization, perennial grass pastures, and moderate grazing of pastures. This information provides a guide for more effective implementation of management systems to meet multiple goals of profit, production, and environmental protection.

Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil and Tillage Research* 83:120-147.

- **Environmental controls on soil and whole-ecosystem respiration for a tallgrass prairie ecosystem.** Information on C flux in grasslands, and its control mechanisms, is needed to quantify GHG emissions and potential C sequestration. Nocturnal CO_2 flux from soil and from plants plus soil was determined 79 times during a two-year period in a Kansas tallgrass prairie ecosystem. Water-filled pore space and soil temperature interacted significantly to control the majority of soil and whole-ecosystem respiration in a similar manner. The contribution of soil respiration could be effectively separated from whole-ecosystem respiration through predictions with regression equations developed and measurement of environmental (i.e., SOC, soil temperature, and water-filled pore space) and physiological (i.e., plant growth rate) controls on soil C dynamics.

Franzluebbers, K., A.J. Franzluebbers, and M.D. Jawson. 2002. Environmental controls on soil and whole-ecosystem respiration from a tallgrass prairie. *Soil Science Society of America Journal* 66:254-262.

- **Winter CO_2 fluxes in humid-temperate pastures**. Although CO_2 uptake by grazing lands during the growing season can be substantial, losses during winter months reduce annual sequestration, potentially turning grazing lands into net C sources. The magnitude of winter fluxes in humid-temperate pastures in the northeastern US was quantified using eddy covariance techniques. Cumulative efflux for the winter months (1 Dec to 31 Mar) averaged 96 g C m^{-2}. Eddy covariance measurements estimated that photosynthetic CO_2 uptake occurred in the absence of snow cover, at temperatures below 0°. Canopy and leaf chamber measurements in the field and in controlled environments suggested minimum temperatures for photosynthetic CO_2 uptake of about -4° C. Even when daytime uptake occurred, nighttime efflux from the system was greater than uptake, such that the pastures remained CO_2 sources throughout the winter.

Skinner, R.H. 2007. Winter carbon dioxide fluxes in humid-temperate pastures. *Agric. Forest Meteoro*l. 144:32-43.

- **Accelerated C loss to respiration limits carbon sequestration on grassland at elevated CO_2**. The CO_2 uptake and release on central Texas grassland exposed to CO_2 levels that spanned pre-Industrial (subambient) to current elevated concentrations was measured to determine how atmospheric CO_2 affects respiration and its sensitivity to seasonal changes of photosynthesis. Respiration rates were greater on grassland at elevated CO_2 levels than subambient CO_2 levels because both C input (net photosynthesis) and respiration per unit of C input increased with CO_2 concentration. By increasing respiration rates, CO_2 enrichment may reduce the net amount of C that plants remove from air and retain in terrestrial ecosystems.

Polley, H.W., W.A. Dugas, P.C. Mielnick, and H.B. Johnson. 2007. C_3-C_4 composition and prior carbon dioxide treatment regulate the response of grassland carbon and water fluxes to carbon dioxide. *Functional Ecology* 21: 11-18.

Polley, H.W., P.C. Mielnick, W.A. Dugas, H.B. Johnson, and J. Sanabria. 2006. Increasing CO_2 from subambient to elevated concentrations increases grassland respiration per unit of net carbon fixation. *Global Change Biology* 12: 1390-1399.

- **Grazing management influences soil C storage differently among three Great Plains rangelands.** Rangelands cover approximately 40% of the earth's land surface, implying that modest changes of C storage in rangeland ecosystems have the potential to modify the global C cycle. Livestock grazing is the prevalent land use of rangelands and has the potential to substantially alter C storage by altering rates of C cycling in grazed ecosystems. Research using comparisons of grazed/ungrazed sites at three locations along an environmental gradient in the Great Plains showed differences of the response of C storage to livestock grazing with semi-arid, shortgrass steppe grazed sites exhibiting 31% more SOC storage compared to ungrazed sites, whereas more mesic grazed sites in the mixed-grass and tallgrass prairies had slightly lower (4-7%) C storage compared to ungrazed sites. The magnitude and proportion of fine root mass within the upper soil profile is likely a principal driver mediating the effect of community composition on the cycling and storage of C in these grassland ecosystems.

Derner, J. D., T. W. Boutton, and D. D. Briske. 2006. Grazing and Ecosystem Carbon Storage in the North American Great Plains. *Plant and Soil* 280:77-90.

Potter, K. N. and J. D. Derner. 2006. Soil Carbon Pools in Central Texas: Prairies, Restored Grasslands and Croplands. *Journal of Soil and Water Conservation* 61:124-128.

Derner, J. D. and G. E. Schuman. 2007. Carbon Sequestration and Rangelands: A Synthesis of Land Management and Precipitation Effects. *Journal of Soil and Water Conservation* 62:77-85.

Derner, J. D., G. E. Schuman, M. Jawson, S. R. Shafer, J. A. Morgan, H. W. Polley, G. B. Runion, S. A. Prior, H. A. Torbert, H. H. Rogers, J. Bunce, L. Ziska, J. W. White, A. J. Franzluebbers, J. D. Reeder, R. T. Venterea, and L. A. Harper. 2005. USDA-ARS Global Change Research on Rangelands and Pasturelands. *Rangelands* 27:36-42.

- **Grazing management can increase soil organic C storage in semi-arid rangelands, but weather must be considered**. Currently recommended grazing practices in northern mixed-grass prairie and shortgrass steppe rangelands have been shown to increase C sequestration significantly over non-grazed pastures. Grazing management can affect soil C levels through changes in the plant community, which can alter turnover of fine roots into SOM, and alterations in the microbial community structure. However, soil C is also strongly influenced by weather. Thirty percent of the C sequestered in a northern mixed-grass prairie from 1982-1992 was subsequently lost during the period 1993-2003 in heavily grazed pastures due to drought. This research has shown that well-managed semi-arid grasslands of the western Great Plains have the potential to sequester significant amounts of C, given enabling weather patterns.

Bowman, R. A., J. D. Reeder, and B. J. Weinhold. 2002. Quantifying Laboratory and Field Variability to Assess Potential for Carbon Sequestration. *Communications in Soil Science and Plant Analyses* 33(9&10):1629-1642.

Derner, J. D. and G. E. Schuman. 2007. Carbon Sequestration and Rangelands: A Synthesis of Land Management and Precipitation Effects. *J. Soil and Water Cons*. 62: 77-85.

Ganjegunte, G. K., G. F. Vance, C. M. Preston, G. E. Schuman, L. J. Ingram, P. D. Stahl, and J. M. Welker. 2006. Soil Organic Carbon Composition in a Northern Mixed-Grass Prairie: Effects of Grazing. *Soil Science Society of America Journal* 69:1746-1756.

Ingram, L. J., P. D. Stahl, G. E. Schuman, G. F. Vance, G. K. Ganjegunte, J. Buyer, J. D. Derner, and J. W. Welker. Grazing and Drought Affects on Carbon, Nitrogen and Microbial Communities in a Mixed Rangeland. *Soil Sci. Soc. Am. J*. (in press)

Miyamota, D.L., R.A. Olson, and G.E. Schuman. 2004. Long-term effects of mechanical renovation of a mixed-grass prairie: I. Plant response. *Arid Land Research and Management* 18:93-101.

Miyamota, D.L., R.A. Olson, and G.E. Schuman. 2004. Long-term effects of mechanical renovation of a mixed-grass prairie: II. Carbon and nitrogen balance. *Arid Land Research and Management* 18:141-151.

Reeder, J. D. and G. E. Schuman. 2002. Influence of Livestock Grazing on C Sequestration in Semi-Arid Mixed-Grass and Short-Grass Rangelands. *Environmental Pollution* 116(3):457-463.

Reeder, S. J., G. E. Schuman, J. A. Morgan, and D. R. Lecain. 2004. Response of Organic and Inorganic Carbon and Nitrogen to Long-Term Grazing of the Shortgrass Steppe. *Environmental Management* 33(4):485-495.

Schuman, G.E., L.J. Ingram, P.D. Stahl, J.D. Derner, G. F. Vance, and J. A. Morgan. Influence of Management on Soil Organic Carbon Dynamics in Northern Mixed-Grass Rangeland. In: R. Lal and R. F. Follett (eds.) *Soil Carbon Sequestration and the Greenhouse Effect*. Soil Sci. Soc. Am. Special Publ. No. 57, Second Edition, Soil Sci. Soc. Am., Madison, WI. (In press).

Schuman, G. E., H. H. Janzen, and J. E. Herrick. 2002. Soil Carbon Dynamics and Potential Carbon Sequestration by Rangelands. *Environmental Pollution* 116:391-396.

- **Inter-seeding alfalfa enhances forage production and C storage in northern mixed-grass rangelands.** Inter-seeding alfalfa into rangelands is an accepted method of range improvement to increase forage production and forage quality through N fixation by legumes. Research was initiated in 2001 to examine the long-term effects of inter-seeding yellow-flowered alfalfa (*Medicago sativa ssp. falcata*) into northern mixed-grass rangelands. Soil fertility, forage production and forage quality were assessed on sites inter-seeded in 1965, 1987, and 1998, and compared to adjacent native rangelands. Nitrogen fixation by the 'falcata' alfalfa led to significantly higher soil N and increased forage production and crude protein concentrations in the inter-seeded treatments. Improved soil N and increased forage production also led to greater soil organic C storage in the inter-seeded areas. SOC in the 1965, 1987, and 1998 inter-seeded sites was 17, 8, and 4% higher, respectively, compared to adjacent native rangelands. This research has shown that the practice of inter-seeding yellow-flowering alfalfa into rangelands is sustainable over decades and will increase forage production, forage quality, and enhance soil C storage in the Northern Great Plains.

Mortenson, M. C., G. E. Schuman, and L. J. Ingram. 2004. Carbon Sequestration in Rangelands Interseeded with Yellow-Flowering Alfalfa (Medicago sativa ssp. falcata). *Environmental Management* 33(supplement):S475-S481.

Mortenson, M. C., G. E. Schuman, L. J. Ingram, V. Nayigihugy, and B. W. Hess. 2005. Forage Production and Quality of a Mixed-Grass Rangeland Interseeded with Medicago sativa ssp. falcata. *Rangeland Ecology and Management* 58:505-513.

Topic: Plantation Tree Farming

Goals: Assess the impacts of intensive tree farm management on the amount and longevity of soil C storage, including soil C changes and storage in below-ground tissues or removed as products; quantify evapotranspiration and optimize water management for desired system outcomes; quantify the C cycle time scales for all tree-derived products; provide policymakers with accurate and current data to establish C credits for tree farm plantations; and address needs for increased productivity, waste utilization, and below-ground responses, including C storage.

Projected Impact: Increased productivity of the Nation's tree farms; meeting increasing demands for wood and fiber; increased C storage to mitigate rising atmospheric CO_2 concentration; and reduced pressure on sensitive lands, thus allowing them to be removed from traditional forest production.

Summary: Intensively managed tree farms and forest plantations are a means of storing atmospheric C in biomass and soils for years to decades, depending upon the specific goals of management (e.g., biofuels, pulp, and/or timber). Elevated atmospheric CO_2 affects both the quantity and quality of plant tissues, which impacts the cycling and storage of C. Although soil CO_2 efflux increased significantly (26.5 %) in a model regenerating longleaf pine community when exposed to elevated CO_2, atmospheric CO_2 enrichment increased biomass, resulting in an increase of 13.8 Mg C ha^{-1} stored in the system. Incubation of soil samples from this study showed that exposure to elevated CO_2 decreased C turnover, indicating that soil C sequestration is likely for longleaf pine ecosystems. Therefore, while increasing levels of atmospheric CO_2 will increase the feedback of CO_2 to the atmosphere via soil efflux, forest ecosystems remain potential sinks for atmospheric CO_2 due to greater biomass production and greater potential for soil C storage.

Selected Accomplishments

- **Effects of elevated atmospheric CO_2 on competition in a model longleaf pine community.** A model regenerating longleaf pine community was exposed to two CO_2 regimes (ambient, 365 ppm and elevated, 720 ppm) for three years. Total above- and belowground biomass was 70% and 49% greater, respectively, in CO_2-enriched plots; C content followed a similar response pattern which resulted in an increase of 13.8 Mg C ha^{-1} under elevated CO_2. Responses of individual species, however, varied: longleaf pine (*Pinus palustris*) was primarily responsible for the positive response to CO_2 enrichment; wiregrass (*Aristida stricta*), rattlebox (*Crotalaria rotundifolia*), and butterfly weed (*Asclepias tuberosa*) exhibited negative above- and belowground biomass responses to elevated CO_2, while sand post oak (*Quercus margaretta*) did not differ significantly between CO_2 treatments. These differential individual responses resulted in alterations in community structure under high CO_2. Therefore, while longleaf pine may perform well in a high CO_2 world, other members of this community may not compete as well, which could alter community function. Effects of elevated CO_2 on plant communities are complex, dynamic, and difficult to predict, clearly demonstrating the need for more research. .

  Davis, M.A., S.G. Pritchard, R.J. Mitchell, S.A. Prior, H.H. Rogers, and G.B. Runion. 2002. Global Climate Change and Community Structure: Effects of Elevated Atmospheric CO_2 on Competition in a Model Longleaf Pine Community. *Journal of Ecology* 90:130-140.

  Runion, G.B., M.A. Davis, S.G. Pritchard, S. A. Prior, R.J. Mitchell, H.A. Torbert, H.H. Rogers, and R.R. Dute. 2006. Effects of Elevated Atmospheric CO_2 on Biomass and Carbon Accumulation in a Model Regenerating Longleaf Pine Ecosystem. *Journal of Environmental Quality* 35:1478-1486. 2006.

- **Nitrogen and C cycling in a model longleaf pine community as influenced by increased atmospheric CO_2.** This work examined responses to elevated CO_2 in a typical regenerating longleaf pine-wiregrass community. The model community consisted of five plant species: (1) an evergreen conifer (*Pinus palustris*), (2) a bunch grass (*Aristida stricta*), (3) a broadleaf tree (*Quercus margaretta*), (4) a perennial herbaceous legume (*Crotalaria rotundifolia*), and (5) a herbaceous perennial (*Asclepias tuberosa*) grown at two CO_2 levels (ambient and twice ambient). The CO_2-enriched plots had greater aboveground biomass than ambient plots, mainly due to increased pine growth. After 3 years, samples of the soil were collected from 0-5, 5-10, and 10-20 cm depth increments. Microbial respiration, potential C and N mineralization, and C turnover were measured during a 120-day incubation of the soil samples. Elevated CO_2 decreased soil C respiration and C turnover, but increased N mineralization. Results indicate that soil C sequestration is likely for soil in this longleaf pine ecosystem.

  Torbert, H.A., S.A. Prior, G.B. Runion, M.A. Davis, S.G. Pritchard, and H.H. Rogers. 2004. Nitrogen and Carbon Cycling in a Model Longleaf Pine Community as Affected by Elevated Atmospheric CO_2. *Environmental Management* 33 (Supplement 1):132-138.

Topic: Organic Carbon Transformations

Goals: Determine factors controlling the rate, mass, and timing of CO_2 sequestered by plants; determine the amounts and biochemical composition of plant compounds partitioned to above- and below-ground plant organs; determine the fate of plant C within the soil, including the spatial distribution of plant C originating from above- and below-ground plant organs; determine the processes involved in the physical, chemical, and biological decomposition and transformations of plant-derived C; determine the rate of production and turnover of short-, intermediate-, and long-term soil C pools; determine the processes and mechanisms of soil C loss and transport, including understanding of on-site and off-site impacts; and determine the impact of elevated atmospheric CO_2 and climate change on biochemical composition and changes in plant structure and on soil C storage processes.

Projected Impact: New management practices enabling enhanced soil and plant productivity with maximum soil C storage.

Summary: Plant roots contribute more to SOC than do aboveground plant parts, even when aboveground organs are buried through tillage, which is due partially to rhizodeposition and to differences of organ composition. Short-term decomposition kinetics are more readily predicted by initial plant composition than are kinetics after 120 d. Management practices (e.g. land use, tillage) interact to alter the rate and location soil C storage. Erosion displaces and redistributes soil C, such that some areas accrete C. Elevated CO_2 enhancement of non-biomass yield may also increase soil C content and improve soil properties.

Selected Accomplishments

- **Soil physical properties in CO_2 enriched agroecosystems**. Increasing biomass of crops exposed to elevated atmospheric CO_2 suggests the delivery of more C to soils and potential alteration of soil physical properties. Soil samples were taken from the top 6 cm of a loamy sand soil after 5 years of sorghum or soybean production under no-till management at two levels of CO_2—360 ppm (ambient) and 720 ppm (elevated). Soil C content, soil bulk density, saturated hydraulic conductivity, and water stable aggregates were determined. Elevated CO_2 increased soil C content. Significant interactions between cropping systems and CO_2 were noted for soil bulk density and saturated hydraulic conductivity; aggregate stability exhibited a similar trend. The greatest effects were noted in the soybean system. Results indicate that CO_2-induced enhancement of non-biomass yield could increase soil C content leading to improvements of physical properties, especially for soybean production systems.

  Prior S.A., G.B. Runion, H.A. Torbert, and H.H. Rogers. 2004. Elevated Atmospheric CO_2 in Agroecosystems: Soil Physical Properties. *Soil Science* 169 (6):434-439.

- **SOC and N accumulate near the surface of pastures, but not deeper.** SOC and N were measured during a 12-year period in different pasture management systems. Sequestration of C and N occurred only in the top 12 inches of soil. This information will help guide more effective sampling strategies for better estimates of soil C sequestration within cattle grazing systems. Significant sequestration of C in soils under pasture is possible, given that pastures occupy more than 100 million acres in the U.S. alone.

  Franzluebbers, A.J., and J.A. Stuedemann. 2005. Bermudagrass management in the Southern Piedmont USA. VII. Soil-profile organic carbon and total nitrogen. *Soil Science Society of America Journal* 69:1455-1462.

- **Short- and long-term exposure of soil to grasses affects SOM fractions and dynamics.** Tall fescue plants are naturally infected with an endophytic fungus that offers host-plant resistance to environmental and biological stresses and contributes to the accumulation of SOM, either through enhanced plant production and/or through reduced soil microbial activity. Short-term laboratory experiments and long-term field experiments were conducted to determine the changes of SOC and N during growth of fungus-infected and fungus-free tall fescue. SOC and N accumulate in response to the large input from growing and dying roots of pasture grasses. However, there were inconsistent indications that the forms of organic C and N in soil were altered by the presence of the plant fungus, thus questioning the need to manage the fungus as part of a C management strategy.

Franzluebbers, A.J. 2006. Short-term responses of soil C and N fractions to tall fescue endophyte infection. *Plant and Soil* 282:153-164.

Franzluebbers, A.J., and N.S. Hill. 2005. Soil carbon, nitrogen, and ergot alkaloids with short- and long-term exposure to endophyte-free and -infected tall fescue. *Soil Science Society of America Journal* 69:404-412.

Franzluebbers, A.J., and J.A. Stuedemann. 2003. Bermudagrass management in the Southern Piedmont USA. III. Particulate and biologically active soil carbon. *Soil Science Society of America Journal* 67:132-138.

- **Impact of soil erosion on C storage in agricultural ecosystems.** Soil erosion has a well-established negative impact on soil quality and productivity of agricultural lands, but its impact on balance of C stocks within terrestrial ecosystems is unclear. To assess sedimentation impact, a suite of radiometric tracers (^{14}-C, ^{137}-Cs and ^{210}-Pb) were used as chronological tracers to measure dynamics of sediment and C storage within agricultural fields and adjacent riparian wetlands. Modeling the kinetics of C dynamics using these tracers provides strong evidence for accelerated C sequestration associated with soil redistribution on the landscape. On a global basis, it has been estimated that 75 billion tons per year of soil is subject to water erosion, which translates to a displacement of ~0.50 billion tons per year of soil C, thus emphasizing the importance of erosion management for C storage strategies.

McCarty, G. W. and Ritchie, J. C. 2002. Impact of soil movement on carbon sequestration in agricultural ecosystems. *J. Environ. Pollut*. 116:423-430.

Ritchie, J. C. and McCarty, G. W. 2003. Using 137-Cesium to understand soil carbon redistribution on agricultural watersheds. *Soil Till. Res*. 69:45-51.

Ritchie, J. C., and McCarty, G. W. 2004. Using 137 Caesium to understand soil carbon redistribution on agricultural watersheds. Soil and Till. Res. 69:45-51. Venteris, E .R., McCarty, G. W., Ritchie, J. C. and Gish, T. Influence of management history and landscape variables on soil organic carbon and soil redistribution. *Soil Science.* 169:787-795.

Schumacher J. A., Kaspar, T. C., Ritchie, J. C., Schumacher, T. E., Karlen, D. L., Venteris, E. R., McCarty, G. W., Colvin, T. S., Jaynes, D. B., Lindstrom, M. J. and Fenton T. E. 2005. Identifying spatial patterns of erosion for use in precision conservation. *Journal of Soil and Water Conservation*. 60(6):355-361,

Doraiswamy P. C., McCarty, G. W., Hunt E. R. and Yost R. S. 2006. Modeling soil carbon sequestration in agricultural lands of Mali. *Agricultural Systems.* doi:10.1016/j.agsy.2005.09.011,

Ritchie, J. C., McCarty, G. W., Venteris, E. R. and Kasper, T. C. 2006. Soil and soil organic carbon redistribution on the landscape. *Geomorphology*. doi:10.1016/j.geomorph.2006.07.021.

Ritchie J. C., McCarty G. W., Venteris, E. R. and Kasper T. C. 2005. Using sediment budgets to understand soil organic carbon redistribution and budgets, p. 3-8. In: Horowitz, A.J., and Walling D.E. (eds.), *Sediment Budget 2*, International Association of Hydrological Sciences Publication no. 292, IAHS Press, Wallingford, UK, (Peer reviewed book chapter).

Zheng, D., Hunt, E.R. Jr., Doraiswamy, P.C., McCarty, G.W., and Ryu, S.R. 2006. Using remote sensing approach and models to understand the ecology of landscapes. In *Linking Ecology to Landscape Hierarchies* Eds. J. Chen, S.C. Saunders, K.D. Brosofske, T.R. Crow. Nova Science Publishers, Hauppauge NY. pp. 125-166.

- **Estimated minimum above and belowground C inputs for soil organic C maintenance.** A detailed literature review discussed 1) historical aspects of C management in agriculture; 2) estimates of harvest index and root-C to shoot-C ratios of several major crops; 3) estimated total source C production inputs relative to C inputs critical for soil organic C maintenance. Biomass produced and left on the field has increased for the past 60 years, and that together with reduced tillage has resulted in agriculture building SOM, and thus storing C. Knowing how much biomass is available and the minimum amount of C needed to be put into the soil is a critical step in establishing guidelines for harvesting crop biomass. Accurate knowledge of how management decisions affect stored C allows agriculture to reduce negative impacts on global climate changes and improve soil and environmental quality.

  Johnson, J.M.F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agronomy Journal* 98:622-636.

- **Plant quality and decomposition.** Research was conducted to identify stable forms of C and mechanisms to increase stable C inputs to soil. A laboratory study identified how plant chemical composition impacts the rate of residue decay: short-term decomposition kinetics correlate well with plant composition (e.g., C:N ratio, carbohydrates and lignin), but after 120 days, decomposition kinetics correlate poorly with initial plant composition. This information will enable improved mechanistic models that predict how crop residue may contribute to soil C sequestration and will provide the basis for a tool to improve strategies focused on soil C management

  Johnson, J.M.F., N.W. Barbour, and S.L. Weyers. 2007. Chemical composition of crop biomass impacts its decomposition. *Soil Science Society of America Journal* 71:155-162.

Topic: Inorganic C

Goals: Determine the impact of major irrigation projects on inorganic C storage and CO_2 emissions; develop economically viable management practices that could either reduce CO_2 emissions from inorganic C or store CO_2 in the soil water system; determine the rate and quantity of CO_2 released to the atmosphere as a result of liming and gypsum application, and the effect of different management practices on that release; quantify the impact of different fertilizer products on the emission or storage of C in agricultural soils.

Projected Impact: New management practices on irrigated lands will reduce CO_2 emissions or facilitate storage of inorganic C in agricultural soils and hydrologic systems.

Summary: Research in two different ecosystems identified changes of soil inorganic C content as an important contributor to the overall soil and/or ecosystem C balance.

Selected Accomplishments

- **Southwestern U.S. Watersheds a C Source?** Climate modelers and C trading consortiums note that in the world's C budget, about 20% of the CO_2 released to the atmosphere is unaccounted for. With rangelands making up 40+% of the land surface area, they are a potential sink for the unaccounted-for C. Data collected on the ARS Walnut Gulch Experimental watershed and subsequent analysis indicated that the watershed was a source of CO_2 to the atmosphere. The source was hypothesized to be from carbonates in the soils.

  Martens, D.A., Emmerich, W.E., McLain, J.E., Johnsen, T.N., Jr. 2005. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. *Soil and Tillage Res.* 83:95-119.

  Perez-Quezada, J.F., Saliendra, N.Z., Emmerich, W.E., Laca, E.A. 2007. Evaluation of statistical protocols for quality control of ecosystem CO2 fluxes. *J. of the Royal Statistical Society*, Series A. 170(Part 1): 213-230.

- **Long-term rangeland grazing practices may influence both inorganic and organic forms of soil C.** Long-term evaluations on the effects of grazing in rangeland ecosystems are needed to accurately assess the impact of grazing intensity on rangeland health, and to determine the potential role for rangelands to store C. Inorganic C can represent a significant fraction of the total soil C in semi-arid grasslands of the western Great Plains. Investigation of soil C in pastures of shortgrass steppe vegetation which had been grazed at different intensities (light, heavy and no grazing) from 1939 until the present was conducted to determine how these long-term grazing treatments had affected soil C. While the effect of long-term grazing on SOM C was minor, long-term grazing at a heavy stocking rate increased soil inorganic C by 65%, compared to light grazing intensity or non-grazed exclosures. Ignoring inorganic C can result in large errors when estimating the potential for grazing to influence the C cycle, and has spurred new research in labs around the world to consider the role of soil inorganic C in soil C sequestration.

  Reeder, S. J., G. E. Schuman, J. A. Morgan, and D. R. LeCain. 2004. Response of Organic and Inorganic Carbon and Nitrogen to Long-Term Grazing of the Shortgrass Steppe. *Environmental Management* 33(4):485-495.

Topic: Interactions of Carbon and Nitrogen Cycles

Goals: Define cropping systems, by location, that can economically incorporate legumes into the rotation; determine how to promote free-living N-fixing organism in areas or cropping systems not adapted to use of legumes; quantify the acidification that occurs during the oxidation of organic sources of N in the presence of growing crops; quantify the impacts of plants grown with elevated CO_2 on plant protein (N) content and on N requirements for decomposition; determine the effects of elevated CO_2 on the processes and mechanisms of soil C and N interactions; and determine the duration and magnitude of interference by ammonia-based fertilizer on methane oxidation.

Projected Impact: Increased nitrogen availability to store C in the soil, improved soil productivity, and reduced fossil fuel use for food production.

Summary: Long-term experiments indicated that N fertilizer acidified the topsoil and increased silica solubility and leaching, however, this effect was N-form dependent. Elevated CO_2 does not seem to alter C:N ratio of plant material. Mixed responses were reported on the impact of elevated CO_2 on soil N. However, mesocosm studies demonstrated that elevated CO_2 enhances the infection of host plant roots by beneficial mycorrhizal fungi and that this plant-microbe interaction leads to enhanced N acquisition by the host plant and increased plant residue decomposition.

Selected Accomplishments

- **Decomposition of soybean grown under elevated concentrations of CO_2 and O_3.** A 2-year experiment was conducted to determine the chemistry and decomposition rate of aboveground residues of soybean grown under various combinations of low and high levels of CO_2 and O_3 in open top field chambers. The CO_2 treatments were ambient (370 ppm) and elevated (714 ppm) levels. Ozone treatments were charcoal-filtered air (21 ppb) and nonfiltered air plus 1.5 times ambient O_3 (74 ppb) 12 h day^{-1}. Inhibitory effects of added O_3 on biomass were largely negated by elevated CO_2. C mineralization rates of residues from the elevated gas treatments were not different from the control. However, N immobilization increased in soils containing petiole and stem residues from the elevated CO_2 and O_3 treatments. Mass loss of decomposing leaf residue from the added O_3 and combined gas treatments was 48% less than the control after 20 weeks. Decreased decomposition of leaf residues was correlated with lower starch and higher lignin levels. The main influence of CO_2 and O_3 levels on decomposition processes is apt to arise from effects on residue mass input, which is increased by elevated CO_2 and suppressed by O_3.

  Booker, F.L., S.A. Prior, H.A. Torbert, E.L, Fiscus, W.A. Pursley, and S. Hu. 2005. Decomposition of Soybean

Grown under Elevated Concentrations of CO_2 and O_3. *Global Change Biology* 11:685-698.

- **Elevated CO_2 enhances mycorrhizal fungi-mediated N acquisition in host plants**. Greenhouse mesocosm studies demonstrated that elevated CO_2 enhances the infection of host plant roots by beneficial mycorrhizal fungi and that this plant-microbe interaction leads to enhanced N acquisition by the host plant. Mycorrhizal fungi stimulated decomposition of plant residues as well. In mixed species competition studies, mycorrhizae infection of roots and associated N uptake provided a competitive advantage of forbs over grasses. If similar mycorrhizal fungi–plant responses occur in the field, elevated CO_2 would be expected to increase N uptake by plants in low nutrient soils and cause a shift in species composition in favor of plants infected by mycorrhizal fungi.

Hu, S., Wu, J., Burkey K.O., Firestone, M.L. 2005. Plant and microbial N acquisition under elevated atmospheric CO_2 in two mesocosm experiments with annual grasses. *Global Change Biology* 11: 213-223.

Chen, X., Tu, C., Burton, M.G., Watson, D.M., Burkey, K.O., Hu, S. 2007. Plant nitrogen acquisition and interactions under elevated carbon dioxide: impact of endophytes and mycorrhizae. *Global Change Biology* 13: 1238-1249.

Tu, C., F.L. Booker, D.M. Watson, X. Chen, T.W. Rufty, W. Shi and S. Hu. 2006. Mycorrhizal mediation of plant N acquisition and residue decomposition: impact of mineral N inputs. *Global Change Biology* 12:793-803.

- **Soybean and grain sorghum residue decomposition in a CO_2 enriched production system.** The effects of CO_2 concentration on soybean and grain sorghum residue decomposition were examined using open top field chambers. Mass, C, and N losses from residues were measured using the mesh bag method. The CO_2 concentration had little effect on C:N ratio, probably because the tissue used had senesced, nor did it affect percent residue recovery. Nevertheless, the higher biomass formed under elevated CO_2 resulted in more residue and C remaining after overwintering. Results indicate that under high CO_2 conditions, larger quantities of residue may increase soil C and ground cover by residue. This may enhance soil water storage, improve soil physical properties, and reduce erosion losses.

Prior S.A., H.A. Torbert, G.B. Runion, and H.H. Rogers. 2004. Elevated Atmospheric CO_2 in Agroecosystems: Residue Decomposition in the Field. *Environmental Management* 33 (Supplement 1):344-354.

- **Simulated impact of crop residue on GHG emission.** Maintaining crop production levels while reducing GHG emissions requires strategic residue and N fertilizer management. Long-term ^{15}N field data was used to validate the NCSWAP (Nitrogen and Carbon Cycling in Soil, Water, Air and Plant) model. The predicted denitrification (conversion of N to N_2O form) losses were 39, 46, and 51 lb/acre/year for low N fertilizer rates, and 40, 64, and 77 lb/acre/year for high N fertilizer rates, when the corn residue was returned at 0, 4000 (66%), 6000 (100%) lb/acre rates, respectively. Thirty-year simulation scenarios with the NCSWAP model suggested that residue returned to the plots decreases N leaching but increases denitrification losses.

Gollany, H.T., J.A.E. Molina, C.E. Clapp, R.R. Allmaras, M.F. Layese, J.M. Baker, and H.H. Cheng. 2004. Nitrogen leaching and denitrification in continuous corn as related to residue management. *Environmental Management*, Vol. 33, Supplement 1, pp. S289-S298.

- **Effects of incorporated source C on soluble silica and C storage.** Results from long-term experiments showed that N fertilizer application acidified the topsoil and increased silica (Si) solubility and leaching. The movement and concentration of Si below the topsoil resulted in the development of a hard layer below the plow depth that reduced water infiltration. A long-term wheat-fallow experiment with several crop residue management practices, three N rates, and two organic amendments was established in 1931. SOC storage for the manure treatment was 25% higher than for the fall burned wheat residue treatment without N fertilization. In the top 20 inches of soil, N fertilizer application decreased water-soluble Si by 17% while applied manure or pea vines increased water-soluble Si by 10%. It is likely the occluded SOC in phytoliths reduced the siliceous surface available for dissolution.

Gollany, H.T., R.R. Allmaras, S.M. Copeland, S.L. Albrecht, and C.L. Douglas. 2006. Incorporated Source Carbon and Nitrogen Fertilization Effects on Carbon Storage and Soluble Silica in a Haploxeroll. *Soil Science* 171:585-597.

- **Influence of atmospheric CO_2 on soil C.** Carbon sequestration in soil depends on how cycles of N and other essential elements respond to CO_2. Changes in soil C storage and N cycling were measured in a central Texas grassland that was exposed for 4 years to CO_2 concentrations ranging from pre-Industrial levels to elevated concentrations forecast within 50 years. Soil C was lost at lower-than-present CO_2 concentrations, but was unchanged at elevated CO_2 because N availability to plants declined and losses of formerly-stored C offset increases in new C at elevated CO_2. Carbon may have been stored passively in soils as CO_2 rose to the present concentration, but little of the additional C fixed by grassland plants at elevated CO_2 may be sequestered in soil if N is depleted from older SOM to meet the nutritional demands of more rapidly growing plants.

Gill, R.A., L.J. Anderson, H.W. Polley, H.B. Johnson, and R.B. Jackson. 2006. Potential nitrogen constraints on soil carbon sequestration under low and elevated atmospheric CO_2. *Ecology* 87: 41-52.

Gill, R.A., H.W. Polley, H.B. Johnson, L.J. Anderson, H. Maherali, and R.B. Jackson. 2002. Nonlinear grassland responses to past and future atmospheric. *Nature* 417: 279-282.

Topic: Measurement, Validation and Modeling
Goals: Develop tools and techniques to measure C exchange processes and to quantify SOM, soil C, and soil nutrient (e.g., N) storage or loss for major agricultural ecosystems and develop predictive tools to understand, integrate, and predict the impacts of land use, management decisions and global change on soil C storage in agricultural ecosystems from local to national scales.

Projected Impact: Verification of soil C states and processes that enable effective management of soil C and C credit trading.

Summary: New methodologies to measure both total C and various soil C pools were tested against standard methodologies and shown to be rapid, accurate, and much less labor-intensive than standard wet-chemistry procedures. Initial experiments based on gamma-ray spectroscopy induced by inelastic neutron scattering demonstrated the feasibility and accuracy of this approach. The use of diffuse mid-infrared and near-infrared techniques enables rapid measurement of soil C and showed that results from mid-infrared are more accurate and robust for assessing soil composition. Research on soil sampling protocols for accurately measuring changes in soil C and accounting for spatial variation was evaluated, and showed that the cost for sampling can hinder measurements. Research advances in modeling soil C sequestration both at the local and regional scales were successfully evaluated. The EPIC model was used to simulate conservation tillage, cropping system intensification, sod-based crop rotations, and judicious use of fertilizers and herbicides to demonstrate successfully some of the agricultural practices shown to increase SOC. These studies were conducted in crop areas of the southeast and mid-west US. Remote sensing techniques were developed to provide spatial inputs to models, and methods for mapping residue cover and tillage practices were successfully evaluated. A simple model (CQESTR) developed by ARS for predicting soil C from various management practices at field scale was successfully evaluated with long-term field data.

Selected Accomplishments

- **Non-destructive system for analyzing soil C**. The pressing need to assess soil C stocks on local , regional , and global scales is hindered by methodological limitations. A new assessment method based on gamma-ray spectroscopy induced by inelastic neutron scattering (INS) is *in situ*, non-destructive, multi-elemental, and can be used in stationary- or continuous-scanning modes. Data acquired from a soil mass of a few hundreds of kilograms to an approximate depth of 30 cm can be reported immediately. Initial experiments have demonstrated the feasibility of the approach: a linear response was obtained with C concentration, with a detection limit between 0.5 to 1% C by weight.

Wielopolski, L., I. Orion, G. Hendrey, and H. Rogers. 2000. Soil Carbon Measurements Using Inelastic Neutron Scattering. *IEEE Trans. on Nuclear Science* 47:914-917.

- **SOC sequestration with conservation-tillage management in southeastern U.S.**. The recently modified decision support system EPIC v. 3060 was tested against (a) a simpler decision support tool currently used by the USDA-NRCS to identify soil management systems contributing to improved soil quality, and (b) against five years of crop yield and soil data collected from a corn–cotton rotation in central Alabama. No-till management of cotton with a wheat cover crop and other crop rotations with high-residue producing crops increased soil C. Predictions of SOC at the end of five years for the different management schemes were very reasonable, although estimated distribution with depth and within various fractions of organic matter were unsatisfactory. The EPIC model could be a reasonably accurate tool for predicting yield and environmental consequences for over 10 million acres of corn and cotton land of the southeastern U.S.

Abrahamson, D.A., M.L. Norfleet, H.J. Causarano, J.R. Williams, J.N. Shaw, and A.J. Franzluebbers. 2007. Effectiveness of the soil conditioning index as a carbon management tool in the southeastern USA based on comparison with EPIC. *Journal of Soil and Water Conservation* 62:94-102.

Causarano, H.J., J.N. Shaw, A.J. Franzluebbers, D.W. Reeves, R.L. Raper, K.S. Balkcom, M.L. Norfleet, and R.C. Izaurralde. 2007. Simulating field-scale soil organic carbon dynamics using EPIC. *Soil Science Society of America Journal* 71: 1174-1185

- **Using diffuse mid-infrared spectroscopy (MIRS) and near-infrared spectroscopy (NIRS) for soil property measurements.** Although NIRS has been widely evaluated, the utility of MIRS is largely unknown. It was demonstrated that MIRS is more accurate and robust than NIRS for the determination of soil composition. Recent efforts have also focused on assessing the feasibility of on-site determinations using field portable instrumentation. A recent international assessment has shown that *in situ* measurements are practical. The ability of both NIRS and MIRS to map the C concentrations in fields was demonstrated, with use of MIRS found to be more accurate. If calibrated properly, these rapid spectral methods can largely replace chemical based methods. Use of these new measurement technologies will enable better monitoring of C sequestration in agricultural production systems and thereby better enable C credit accounting.

Reeves, III, J. B., McCarty, G. W. and Mimmo, T. V. 2002. The potential of diffuse reflectance spectroscopy for the determination of carbon inventories in soils. *J. Environmental Pollution*. 116(1001):S277-S284.

McCarty, G. W., Reeves, III, J. B. , Reeves, V. B., Follett, R. F. and Kimble, J. M. 2002. Mid-infrared and near-infrared diffuse reflectance spectroscopy for soil carbon measurement. *Soil Science Society of America J*. 66:640-646.

Mimmo, T., Reeves, III, J. B. , McCarty, G. W. and Galletti, G. C. 2002. Determination of biological measures by mid-infrared diffuse reflectance spectroscopy in soils within a landscape. *Soil Science*. 167:281-287.

Reeves, III, J. B., Francis, B.A. and Hamilton, S.K. 2005. Specular reflection and diffuse reflectance spectroscopy of soils. *Applied Spectrosc*. 59:39-46.

Siebielec, G. W., McCarty, G. W., Stuczynski, T. I. and Reeves, III, J. B. 2004. Near- and mid-infrared diffuse reflectance spectroscopy for measuring soil metal content. *J. Envir. Quality.* 33:2056-2069.

Reeves, III, J. B., Follett, R. F., McCarty, G. W. and Kimble, J. M. 2006. Can near- or mid-infrared diffuse reflectance spectroscopy be used to determine soil carbon pools?. *Comm. In Soil Science and Plant Analysis*. 37:2307-2325.

Madari, B. E., Reeves, III, J. B., Machado, P. L. O. A., Torres, E., Guimaraes, G. M. and McCarty, G. W. 2006. Mid- and near-infrared spectroscopic assessment of soil compositional parameters and structural indices in two ferralsols. *Geoderma*: 136:245-259.

McCarty, G. W. and Reeves, III., J. B. 2006. Comparison of Near Infrared and Mid Infrared Diffuse Reflectance Spectroscopy for Field Scale Measurement of Soil Fertility Parameters. *Soil Science*: 171:94-102.

Madari, B. E., Reeves, III, J. B., Coelho, M. R., Machado, P. L. O. A., De-Polli, H., Coelho, R. J., Benites, V. M., Souza, L. F. and McCarty, G. W. 2005. Mid- and near-infrared spectroscopic determination of total and organic carbon in a diverse set of soils from the Brazilian national soil collection. *Spectroscopy Letters*. 38:721-740.

Sarkhot, D. V., Comberford, N. B., Jokela, E. J. and J. B. Reeves. 2007. Effects of forest management intensity on carbon and nitrogen content in different soil size fractions of a north Florida spodosol. *Plant and Soil*. 294:291-303.

Reeves, III, J. B. and McCarty, G. W. 2006. Spectroscopic methods for soil carbon assessment. In R. Lai. *Encyclopedia of Soil Science*. CRC Press. Volume 2:1678-1681.

- **Development of decision support tools for C management.** Land cover/land use, crop residue and tillage practices derived from satellite imagery are being used with ground-based models to simulate changes in soil C resulting from different management practices. The simulations are being conducted across the US Corn Belt and changes monitored over a 50-year period between 1970-2020. Tillage practices are changing gradually, from total conventional in 1985 to current adoption of reduced till and no-till. The simulations suggest gradual restoration or increase of soil C with conversion to conservation tillage. The calibrated model has been incorporated into a web-based decision support system for optimizing soil C management.

Doraiswamy, P.C., McCarty, G.M., Hunt, E.R., Yost, R., M. Doumbia, M., and Franzluebbers, A.J. 2007. Modeling of Soil Carbon Sequestration in Agricultural Lands of Mali. *Agricultural Systems*, Vol. 94(1), 63-74.

- **New Remote Sensing Tools for Managing Soil Residue Cover and Soil C.** Traditional methods of measuring residue cover are best suited for a few individual fields, but are too labor-intensive for regional surveys. A physically-based, remotely-sensed cellulose absorption index was developed that is linearly related to crop residue cover. Conventional and conservation tillage classes were correctly identified in over 80% of fields in test sites in Maryland, Indiana, and Iowa. Regional surveys of crop residue management practices that affect soil conservation and soil C appear possible using advanced imaging systems. Efficient monitoring technologies to measure crop residues in production fields will improve our ability to detect tillage intensity and provide assessment tools for monitoring impacts of crop residue harvesting for bioenergy production.

Barnes, E. M., Sudduth, K. A., Hummel, J. W., Lesch, S. M., Corwin, D. L., Yang, C., Daughtry, C. S. T., and Bausch, W. C. 2003. Remote- and ground-based sensor techniques to map soil properties. *Photogrammetric Engineering and Remote Sensing* 69:619-630.

Nagler, P. L., Inoue, Y., Glenn, E. P., Russ, A. L, Daughtry, C. S. T. 2003. Cellulose absorption index (CAI) to quantify mixed soil-plant litter scenes. *Remote Sensing of Environment* 87:310-325.

Daughtry, C. S. T., Hunt Jr., E. R., and McMurtrey III, J. E. 2004. Assessing crop residue cover using shortwave infrared reflectance. *Remote Sensing of Environment* 90:126-134.

Daughtry, C. S. T., Hunt Jr., E. R., Doraiswamy, P. C., and McMurtrey III, J. E. 2005. Remote sensing the spatial distribution of crop residues. *Agronomy J*. 97:864-871.

McMurtrey, J. E., Daughtry C. S. T., Devine, T. E., and Corp, L. A. 2005. Detection of crop residues in conventional and large biomass soybeans using a cellulose absorption index. *Agronomy for Sustainable Development* 25:25-34.

Daughtry, C. S. T., Doraiswamy, P. C., Hunt Jr., E. R., Stern, A. J., McMurtrey III, J. E., and Prueger, J. H. 2006. Assessing crop residue cover and soil tillage intensity. *Soil and Tillage Research*. 91:101-108.

- **A C balance model for evaluating C storage or loss**. A C balance model, CQESTR, was developed for nationwide use to assess long-term effects of management, cropping systems, or crop residue removal on SOC storage/loss in agricultural soils. CQESTR uses crop rotation, yield, tillage information, and weather data to compute the rate of biological decomposition of crop residue or organic amendments as they convert to SOC. The rate of decomposition is a function of cumulative degree days, water availability, N content of residue, and soil properties.

Rickman, R., C. Douglas, S. Albrecht, and J. Berc. 2002. Tillage, crop rotation, and organic amendment effect on changes in soil organic matter. *Environmental Pollution*. 116:405-411.

- **Spatial variation of soil C in a sloping agricultural landscape**. Soil sampling for accurately measuring soil C increases must account for spatial variation. Geostatistical analysis indicated that sampling on 10 m or smaller intervals is needed to adequately account for spatial variation in a highly variable central Pennsylvania landscape. The cost of necessary soil sampling and analysis could hinder farmer participation in C credit programs if measured verification via in situ sampling, rather than modeled prediction, is required.

C.J. Dell and A.N. Sharpley. 2006. Spatial variation of soil organic carbon in a northeastern U.S. watershed, *Journal of Soil and Water Conservation* 61, 129-136.

- **Promising new technologies for measuring total soil C.** New methodologies have the capability to measure a number of soil C pools, are efficient, less labor-intensive, and have the potential to be adopted for future production-level analyses. Mid- and Near-Infrared show much promise. Pyrolysis Molecular Beam Mass Spectrometry allows determination of pool sizes and can provide insight about the organic molecular forms of C found within various soil C pools.

Magrini, K.A.*, R.F. Follett, J.M. Kimble, M.F. Davis, and E.G. Pruessner. 2007. Using Pyrolysis Molecular Beam Mass Spectrometry (MBMS) to Characterize Soil Organic Carbon in Native Prairie Soils. *Soil Science*. 172:659-672.

Reeves, J.B. III, R.F. Follett, G.W. McCarty, and J.M. Kimble. 2007. Can Near- or Mid-Infrared Diffuse Reflectance Spectroscopy be used to determine soil carbon pools? *Communications in Soil and Plant Analysis* 37:2307-2325.

Reeves, J.B. III., R.F. Follett, G.W. McCarty, and J.M. Kimble. 2006. Can Near or Mid-Infrared Diffuse Reflectance Spectroscopy Be Used to Determine Soil Carbon Pools? *Communications in Soil Science and Plant Analysis*, 37: 1–19.

Reeves, J.B. III., G.W. McCarty, R.F. Follett, and J.M. Kimble. 2006. The potential of spectroscopic methods for rapid analysis of soil samples. pp. 423-442. In R. Lal, C. Cerri, M. Bernoux, J. Etchevers, and E. Cerri (eds.). *Carbon Sequestration in Soils of Latin America*. Haworth Press, Inc. Binghamton, NY.

Qian, Y.L., R.F. Follett, S. Wilhelm, A.J. Koski, and M.A. Shahba. 2004. Carbon isotope discrimination of three Kentucky bluegrass cultivars with contrasting salinity tolerance. *Agron. J*. 96:571-575.

McCarty, G.W., J.B. Reeves III, V.B. Reeves, R.F. Follett and J.M. Kimble. 2002. Mid-Infrared and Near-Infrared Diffuse Reflectance Spectroscopy for Measurement of Carbon in Soils. *Soil Sci. Soc. Amer. J*. 66:640-646.

Follett, R.F. and E.G. Pruessner. 2000. Interlaboratory carbon isotope measurements on five soils. In R. Lal, J.M. Kimble, R.F. Follett and B.A.Stewart (eds) p. 185-192. *Methods of Assessment of Soil Carbon*. CRC Press, Boca Raton, FL.

Component II: Trace Gases

Topic: Cropping Systems

Goals: Develop productive management practices that minimize trace gas emissions; quantify the relationship between soil C storage and trace gas flux; provide information to improve national trace gas inventories; quantify the role of buffer and riparian zones on trace gas exchange; quantify the impact of increasing CO_2 concentrations on trace gas exchange within crop production systems.

Projected Impact: Decreased greenhouse gas emissions without adverse effects on productivity.

Summary: The core project, GRACEnet, provides a framework for elucidation of the complex interactions of soil, management, and environmental factors influencing trace gas emissions from a variety of cropping systems. The need for trace gas emissions data as a function of production system was addressed with measurements from cropping systems across the US using common methodology. This effort has: i) enabled the expansion of the cropping component of the national GHG (trace gas) inventory, ii) provided insights needed to stimulate efforts to develop cropping systems that reduce trace gas emissions, provided data for the evaluation trace gas emissions models, and resulted in improved methodology for measurement of trace gas emissions.

Selected Accomplishments

- **Improved models and measurement methods**. Accurate measurements of tillage-induced gas fluxes are needed to quantify the effects of different tillage operations on C sequestration by agricultural soils. A more robust form of gas collection and measurement using the chamber method resulted in improved data quality when sampling gas flux from soil surfaces. Sampling techniques and mathematical methods were adapted for measurements from confined animal feeding operations (CAFOs). Data were collected from tethered sampling devices using a boundary layer sampling methodology. Efforts continued to refine the DAYCENT model, which has potential applications from field to regional scale or higher. These results collectively enabled more accurate quantification and characterization of trace gas emissions from agriculture, important steps needed for emission control and accounting technologies suitable for C credit trading. A better understanding of multiple and interacting factors affecting gas fluxes can serve as the basis to formulate policies that favor increased C sequestration in agricultural production.

Adler P.R, S.J. Del Grosso, and W.J. Parton. 2007. Net greenhouse-gas flux for bioenergy cropping systems. *Ecological Applications* 17:675-691.

Livingston, G.P., G.L. Hutchinson, and K. Spartalian. 2006. Trace gas emission in chambers: a non-steady-state diffusion model. *Soil Science Soc. Amer. J.* 70:1459-1469.

Del Grosso, S.J., A.R. Mosier, W.J. Parton and D.S. Ojima. 2005. DAYCENT model analysis of past and contemporary soil N_2O and net greenhouse gas flux for major crops in the USA. *Soil Tillage and Research* 83:9-24, doi:10.1016/j.still.2005.02.007.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, E.A. Holland, E. Pendall, D.S. Schimel and D.S. Ojima. 2005. Modeling soil CO_2 emissions from ecosystems. *Biogeochemistry* 73:71-91, DOI: 10.1007/s10533-004-0898-z.

Livingston, G.P., G.L. Hutchinson, and K. Spartalian. 2005. *Geophysical Research Letters* 32:L24817, doi:10.1029/2005GL024744.

Rochette, P., Hutchinson, G.L. 2005. Measurement of soil respiration in situ: chamber techniques. American Society of Agronomy Monograph Series No. 47. In *Micrometeorology in Agricultural Systems*, J.L. Hatfield and J.M. Baker (eds). pp. 247-286.

Hutchinson, G.L. and P. Rochette. 2003. Non-flow-through steady-state chambers for measuring soil respiration: Numerical evaluation of their performance. *Soil Science Society of America Journal.* V. 67(1). p. 166-180.

Hutchinson, G.L. and G.P. Livingston. 2002. Soil-atmosphere gas exchange. In Dane, J.H. and G.C. Topp (eds). Soil Science Society of America Book Series: 5, Madison, WI. *Methods of Soil Analysis,* Part 4, Physical Methods. 2002. p. 1159-1182.

Parkin, T.B. 2007. Effect of sampling frequency on estimates of cumulative N2O emissions. *J.Environ Qual.* (In Press)

- **Management and N fertilizer effects on emissions**. The interacting effects of management practices and N fertilizer applications were investigated to identify practices that show promise for controlling trace gas emissions from crop systems. These studies were accomplished in the context of overall N inputs to agricultural systems under a variety of management conditions, with a view to enhancing the efficiency of N use and reducing negative environmental impacts. The research complemented previous studies and provided needed information about agricultural GHG emissions. The impact of this work has been to bring a better understanding of the role of improved N-management on emissions. Control appears possible through the use of tillage practices, controlled-release N-sources, nitrification inhibitors, irrigation, and crop rotations. The use of new measurement and modeling tools aids in the evaluation of gaseous and other N losses.

Liu, X.J., A.R. Mosier, A.D. Halvorson, C.A. Reule, and F.S. Zang. 2007. Denitrification and N_2O emission in arable soils: effect of tillage, N source, and soil moisture. *Soil Biology & Biochemistry* 39: 2362-2370.

Collins, H.P., J.A. Delgado, A.K. Alva, and R. F. Follett. 2006. Use of ^{15}N Isotopic Techniques to Estimate N Cycling from a Mustard Cover Crop to Potatoes. *Agronomy Journal* 99:27-35.

Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. *Jour. Envir. Qual*. 35:1584-1598.

Liu, X.J., A.R. Mosier, A.D. Halvorson, and F.C. Zhang. 2006. The impact of nitrogen placement and tillage on NO, N_2O, CH_4, and CO_2 fluxes from a clay loam soil. *Plant and Soil* 280: 177-188.

Liu, X.J., A.R. Mosier, A.D. Halvorson., and F.S. Zhang. 2005. Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. *Plant and Soil* 276 (1-2): 235-249.

Mosier, A.R., J.K. Syers, and J.R. Freney. 2004. Nitrogen Fertilizer: An essential component of increased food, feed, and fiber production. pp. 3-15 In. A.R. Mosier, J.K. Syers, and J.R. Freney (eds.) *Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment*. SCOPE Volume 65, Island Press, Washington D.C. 296 p.

Mosier, A.R. 2002. Environmental challenges associated with needed increases in global nitrogen fixation. *Nutrient Cycling in Agroecosystems* 63: 101-116.

Mosier, A.R. J.W. Doran, and J.R. Freney. 2002. Managing soil denitrification. *Journal of Soil and Water Conservation* 57:505-513.

Cai, Z. and A.R.. Mosier. 2002. Restoration of CH_4 oxidation abilities of desiccated paddy soils after re-watering. 2002. *Biology and Fertility of Soils*. 36:183-189.

- **Improved knowledge of soil processes results in improved plant N use efficiency and reduction of N_2O**. Nitrogen management has not always been based on sound scientific principles and thus limits development of N_2O emission controls. N_2O is naturally emitted from soils, but the rate of emission increases when N is added as inorganic fertilizer or manure. The developed methodology quantifies how plant and soil N cycles respond to various management techniques (crop rotations, grazing management, soil tillage, etc.). Stable isotopes determined that soil N mineralization of soil N pool was promoted by additions of fertilizer N. The active pool of soil N is composed of amino acids that can be quantified by newly developed techniques. By understanding the potential soil N mineralization rate, the portion of the N supplied by the soil to crop yields can be determined and will result in more precise N fertilization and reduction of N based trace gases. With this knowledge, yields can be increased while reducing fertilizer, operations costs, N_2O emissions, and water quality impacts.

Martens, D.A. and Dick, W.A. 2003. Recovery of fertilizer nitrogen from continuous corn soils under contrasting tillage management. *Biol. Fert. Soil*. 38(3), 144-153.

Martens, D.A. and Loeffelmann K. 2003. Soil amino acid composition quantified by acid hydrolysis and anion chromatography - pulsed amperometry. *J. Agri. Food Chem.* 51, 6521-6529.

Martens, D.A., 2005. Denitrification. *Encyclopedia of Soils in the Environment*, Editor-in-Chief: Daniel Hillel, Elsevier Ltd., Oxford, U.K. © 2005 ISBN (Set): 0-12-348530-4

- **N_2O emissions from Midwest cropping systems.** Soil N_2O emissions from three corn–soybean systems in central Iowa were measured from the spring of 2003 through February 2005 to determine management practice and crop impacts on GHG emissions. The three management systems evaluated were full-width tillage (fall chisel plow, spring disk), no-till, and no-till with a rye winter cover crop. No significant tillage or cover crop effects on N_2O flux were observed for either year. The lack of an observed cover crop effect was in contrast to laboratory experiments that indicated a rye cover crop has potential to reduce N_2O emissions. In the field, fluxes from the corn plots were significantly higher than from the soybean plots for both years. Comparison of the results with estimates calculated using the Intergovernmental Panel on Climate Change default emission factor of 0.0125 indicate that the estimated fluxes underestimate measured emissions by a factor of 3 at the sites, thus raising questions about the adequacy of the emission factor and GHG emissions calculated using the factor. World-wide estimates of GHG emissions may be significantly underestimated for some areas.

Parkin, T.B. and T.C. Kaspar. 2006. Nitrous Oxide Emissions from Corn–Soybean Systems in the Midwest. *J. Environ. Qual*. 35:1496–1506.

Parkin, T.B., T.C. Kaspar, and J.W. Singer. 2006. Cover crop effects on the fate of N following soil application of swine manure. *Plant & Soil*. 289:141–152.

- **Synthesized information to quantify ways to reduce GHG footprint from agriculture.** Producers, policy makers, GHG emitting entities, and C brokers want to use agricultural lands to sequester C and reduce the emission of CO_2, methane and N_2O. However, precise information is lacking on how various management practices across the country increase or reduce net GHG emissions. In addition to ongoing empirical studies, literature was synthesized to assess the current state of knowledge concerning GHG contribution and mitigation potential of agriculture in the central US. This information provides data on the net GHG emissions from specific land management practices, which will likely be region-specific in the US, and is a prerequisite to the widespread adoption of C credit trading, particuliarily a program based on full GHG accounting.

Franzleubbers, A.J., R.F. Follett, J.M.F. Johnson, M.A. Liebig, E.G. Gregorich, T.B. Parkin, J.L. Smith, S.J. DelGrosso, M.D. Jawson, and D.A. Martens. 2006. Agricultural exhaust: A reason to invest in soil. *Journal of Soil and Water Conservation* 61:98-101.

Johnson, J.M.F., Franzluebbers, A.J., Weyers, S.L., Reicosky, D.C. 2007. Agricultural Opportunities to Mitigate Greenhouse Gas Emissions. *Environmental Pollution*. 150:107-124

Johnson, J.M.F., D.C. Reicosky, R.R. Allmaras, T.J. Sauer, R.T. Venterea, and C.J. Dell. 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. *Soil and Tillage Research* 83:73-94.

- **Estimates and inventories of agricultural trace gases.** An inventory of trace gas emissions from crop production systems was conducted and forwarded to EPA to be reported as part of the National GHG Inventory. Assessments were also made at local and regional scales. The inventory used model runs with inputs guided by results of field studies. Improved methods were tested and improvements made through their applications to a range of conditions.

Mosier, A.R., A.D. Halvorson, G.A. Peterson, G.P. Robertson, and L. Sherrod. 2005. Measurement of net global warming potential in three agroecosystems. *Nutrient Cycling in Agroecosystems* 72:67-76.

Bickel, K. (ed). U.S. *Agriculture and Forestry Greenhouse Inventory*: 1999-2001. Contributors: J. Brenner, J. Duffield, R. Follett, L. Heath, J. Kimble, D. Kruger, J. Mangino, A. Mosier, S. Ogle, K. Paustian, H. Shapouri, J. Smith, T. Wirth, and P. Woodbury. Global Change Program Office, Office of the Chief Economist, USDA. Technical Bulletin No. 1907. 164 p. March 2004.

Palm, C.A., J.C. Alegre, L. Arevalo, P. Mutuo, A.R. Mosier, and R. Coe. 2002. Nitrous oxide and methane fluxes in six different land use systems in the Peruvian Amazon. *Global Biogeochemical Cycles* 2002. 16(4), 1073.

- **GHG flux from contrasting management scenarios in the Northern Corn Belt.** Precise information is lacking on how various management systems in the Northern Corn Belt increase or reduce net GHG emissions. Long-term cropping system field plots were established in 2002 in west central Minnesota to compare tillage, rotation and fertilizer treatments and to identify and develop economically viable and environmentally sustainable farming systems. Treatments were selected to represent three different scenarios: "business as usual," "maximum C sequestration" and "optimum GHG benefits." The greatest N_2O flux occurred during spring thaw events, which accounted for 33% to 55% of the flux for 2005 and 2006. Additional events corresponded primarily to N fertilizer events. Under all managements the soil tended to be neutral to slight methane sinks.

- **Comparison of soil C sequestration potential and GHG emissions from alternative land uses in the Northeastern US.** Little information is available about the potential for soil C sequestration and GHG mitigation with the use of alternative crops on Northeastern US dairy farms. A long-term experiment with a dairy forage rotation (corn/soybean/alfalfa), energy crops (switchgrass and reed canary grass), and grazed pasture was established in 2004 at University Park, PA. Findings to date have shown that the energy crops have the lowest N_2O emissions, probably due to highly efficient N uptake by the grasses. Nitrous oxide emissions from pasture and the forage crops were similar when emissions from freshly deposited dung and urine were included in the estimate. With the exception of emission from freshly deposited dung, soils under each of the crops and pasture were a small sink for methane.

<u>*Topic: Enteric Fermentation*</u>

Goals: Develop forage management practices that reduce or minimize methane gas emissions and increase digestible and/or metabolizable energy; develop use and delivery methods for technologies to reduce methane production and increase feedstuffs energy conversion under concentrated and grazing animal production; provide information to improve national trace gas inventories

Projected Impact: Reduced impact of methane emissions on global climate change, and increased animal feedstuff efficiency using less forage land.

Summary: ARS research focused on understanding the microbial ecology of the swine gastrointestinal tract and manure storage pits, identifying the organisms present and determining relevant metabolic activities. This serves as a prelude to the development of methods to promote favorable microbiological changes to reduce undesirable emissions. Enteric methane emissions were reduced with increase of forage quality and grain feeding in a feedlot confinement operation. Additions to grazing animals' diets may increase production efficiency by reducing the energy loss by animals due to methanogenesis if appropriate methods for delivery of the additive are developed. Reductions in animal related methane can improve air quality and reduce associated global warming potential.

Selected Accomplishments

- **Microbial Ecology – Swine Gastrointestinal Tract and Manure Storage Pits**. Utilizing pure culture isolation techniques for anaerobic bacteria as well as culture-independent molecular biological procedures (direct 16S ribosomal RNA gene sequencing), the predominant microbial populations of swine feces and stored manure were identified. The populations were primarily low mole % (G+C) Gram-positive bacteria. Examples of genera identified include *Clostridium*, *Lactobacillus*, and *Streptococcus*. Although in many cases similar to known genera, the large majority of the pure cultures and 16S rDNA sequences could not be identified to the species level, and a number of completely unidentified bacteria were isolated. This work represents the first detailed analyses of the bacterial populations of swine feces and manure. It is difficult to determine changes in bacterial populations in feces and stored manure in response to alterations in diet, pit additives, etc. One approach to determining this change involves using direct 16S ribosomal RNA isolation in group specific amplified ribosomal-DNA restriction analysis (GS-ARDRA). GS-ARDRA was applied to swine fecal and manure storage pit samples obtained on two separate occasions. Fecal and manure storage pit samples obtained on the same day were more similar to each other than to any other samples. Results were consistent with 16S ribosomal DNA sequencing data from bacterial isolates and clones obtained from swine feces and manure storage pit. The GS-ARDRA technique was able to rapidly detect gross bacterial community differences among swine fecal and manure storage pit samples and determine groups of interest for more detailed examination. These results will benefit the scientific community by allowing researchers to rapidly screen a large number of samples and determine which bacterial groups warrant more detailed analysis. Researchers can then develop intervention strategies for reducing emissions by focusing on the predominant bacterial populations in stored swine manure.

  Cotta, M. A., and Whitehead, T. R. 2003. Isolation, Characterization, and Comparison of Bacteria from Swine Feces and Manure Storage Pits. *Environ. Microbiol*. 5:737-745.

  C. J. Ziemer, Cotta, M. A., and Whitehead, T. R. 2004. Application of group specific amplified rDNA restriction analysis to characterize swine fecal and manure storage pit samples. *Anaerobe*. 10:217-227 .

- **Reducing Enteric Emissions from Beef Cattle.** ARS scientists focused on techniques to measure and reduce enteric methane emissions from grazing cattle. Several treatments were studied, including normal medium-quality forage, several types of high-quality forage, forage with a protein ration, and forage with ionophore treatment. Measurements were made using a non-interference technique called the micrometeorological mass-difference (MMD) technique, giving enteric emissions measurements from the animals under normal grazing conditions where grazing selection of herbage was not perturbed. Enteric methane emissions were reduced (in relation to productive gain) with increase in forage quality and grain feeding in a feedlot confinement operation. The addition of an ionophore produced a decrease in methane emissions of 55% compared to a control (medium-quality) grazing situation. Addition of an ionophore to animals receiving a protein supplement produced a decrease of 62%. Addition of ionophores to grazing animals' diet may increase production efficiency by reducing the energy loss by animals due to methanogenesis if appropriate methods for delivery of the additive are developed.

Topic: Waste Management

Goals: Minimize GHG emissions while maintaining effective utilization of animal waste for agriculture; improve the N_2O emission coefficient estimate for manure-fertilized soils; quantify methane and ammonia emissions produced by manure under different management systems.

Projected Impact: Decreased production of greenhouse gases in animal feeding operations.

Summary: Application of animal waste to cropping systems can increase soil trace gas emissions. Investigations have identified potential management systems to minimize trace gas emissions. A rye winter cover crop was found to have potential in mitigating N_2O emissions from soils receiving liquid swine manure. For soils receiving dairy manure, N_2O emissions were lower under conservation tillage management than under conventional tillage. Elevated methane emissions following application of liquid swine manure to soil were attributed to degassing of dissolved methane in the manure. A soil/manure-N interaction was observed to influence soil N_2O emissions. These data can be used to help develop improved inventories of greenhouse gas emissions from land surfaces. These can help policymakers understand the dynamics of greenhouse gas emissions from different systems and indicate potential mitigation strategies. ARS Data has been utilized by the the Division of Air Quality, North Carolina, and the North Carolina State Legislature, by US-EPA and has received international recognition.

Selected Accomplishments

- **The influence of rye cover crop on swine manure-N fate.** Nitrogen balance experiments were conducted in a controlled environment chamber using plastic buckets as the experimental units. Three manure-N loading rates (no manure, low, and high) were applied to soils with and without a rye cover crop. A partial N balance was determined from measurements of nitrate leaching, N_2O and ammonia emissions, cover crop N uptake, and inorganic N remaining in the soil. Cumulative nitrate load in the drainage water was low for rye treatments regardless of the manure rate, however in the fallow treatments, at the high manure rate nitrate leaching losses were large. Rye N uptake was related to manure application rate. Rye had lower cumulative N_2O emission than the no rye treatment for the high manure treatment. Ammonia emissions were low for all treatments during both experiments, which was probably related to the rapid manure incorporation after application. Rye can increase N retention, reduce cumulative N_2O emissions, and reduce cumulative N load in drainage water when manure is applied to soils. Nitrogen balance calculations in the cover crop treatments accounted for less than the equivalent of 50% of the added manure N. We speculate that the living rye plants may have increased immobilization of N in the organic N pools. These results indicate the potential for rye cover crops to reduce N_2O emissions when swine manure slurry is land applied.

  Parkin, T.B., Kaspar, T.C., and J.W. Singer. 2006. Cover Crop Effects on the Fate of N Following Soil Application of Swine Manure. *Plant Soil.* 289:141–152.

- **Non-invasive Measurement of Trace Gas Emissions.** New non-interference micrometeorological measurement techniques were used for evaluation of ammonia, N_2O, and methane emissions from anaerobic lagoons, field applications, and confinement housing. The micrometeorological principles were also used to measure ammonium nitrate and ammonium sulphate aerosol transport in cropping systems and a measurement technique was developed to evaluate ammonia loss during spray application of animal wastes. Systems analyses of the production systems found a significant amount of previously-unknown N emissions from these systems. Based on these findings, procedures were developed for measuring dinitrogen and N_2O production and emissions in anaerobic waste lagoons, which led to the hypothesis of chemical and biological denitrification in these systems. This hypothesis would account for most of the unaccountable N for waste treatment lagoons and for the whole-farm. The first total N mass-balance of a swine feeding operation showed that much of the N entering the swine system left the operation as benign dinitrogen gas instead of air-quality or global-change trace gases. The acquisition of verifiable emissions from these systems allowed ARS scientists, in cooperation with other U.S. and international scientists, to develop models for prediction of ammonia emissions from lagoons and animal housing. These models are being used in lieu of expensive measurement techniques. Ammonia emissions and emission factors derived by ARS research are being used, along with other developed emission factors, by the Division of Air Quality, North Carolina, and the North Carolina State Legislature to enact appropriate laws for regulating trace gas emissions.

Harper, L.A., Sharpe, R.R., and Simmons, J.D. 2004. Ammonia Emissions from Swine Houses in the Southeastern United States. *J. Environ. Qual.* 33: 449-457.

Harper, L. A., Sharpe, R. R., Parkin, T.B., De Visscher, A., van Cleemput, O., and Byers, F.M. 2004. Nitrogen cycling in swine production systems: Ammonia, nitrous oxide, and dinitrogen gas emissions. *J. Environ. Qual*. 33: 1189-1201.

- **Non-invasive Measurement of Trace Gas Emissions:** ARS scientists cooperated with Canadian scientists to optimize the use of tunable diode laser spectroscopy to measure methane and N_2O emissions and to develop a tunable diode laser spectrometer for measuring ammonia. These studies were the first to use non-interference techniques to measure trace gas emissions directly from waste lagoons and showed that previous estimates used by regulatory agencies developed from other measurement techniques were not accurate. These studies were also the first to measure the production of dinitrogen gas by biological or chemical denitrification in anaerobic waste management systems, suggesting that lagoons are not simply “holding structures” for wastes but are treatment facilities as well. To evaluate trace-gas emissions from cropping and animal production systems, many types of gas-concentration and atmospheric-transport technologies must be used. Often, there are no available techniques to evaluate emissions without destroying the emissions source. ARS scientists have cooperated with colleagues from the University of Alberta, CSIRO (Australia), and Agriculture and Agri-Food Canada, to develop new instrumentation for measuring trace-gas concentrations and atmospheric-transport technologies for trace-gas emissions measurement. ARS has worked with other scientists and manufacturers in the development of new sensors to measure trace-gas concentrations under field conditions—such as open and closed-path laser spectrometry. New transport technologies have been developed along with suitable complementary sensors to determine accurate and appropriate emissions. ARS scientists have developed techniques to determine trace gas emissions from animal confinement systems and animals under grazing conditions. These techniques are described in the following sections and include: the micrometeorological mass-difference technique, the integrated horizontal flux technique and the backward Lagrangian stochastic analysis technique. Techniques and instrumentation developed by ARS scientists are currently being used by other scientists to determine trace-gas emissions factors for animal feeding operations in the US and abroad. The animal production industry has recommended use of some of these techniques in the emissions monitoring program associated with the EPA-livestock industry consent decree. The US-EPA has used enteric methane emissions factors determined by ARS to significantly reduce the US inventory contribution of greenhouse gas emissions.

Sharpe, R.R. and Harper, L.A. 2002. Nitrous oxide and ammonia emissions from a soybean field fertilized with swine effluent from a waste holding lagoon. *J. Environ. Qual*. 31:524-532.

- **Micrometeorological Methods:** ARS has been a leading innovator in the development of new atmospheric transport technologies to evaluate trace-gas emissions from animal and cropping systems. ARS scientists have designed a new technology, called the micrometeorological mass difference (MMD) technique, to measure methane emissions from cattle under pasture or feedlot conditions. This technique has been used by ARS, and CSIRO in Australia, to develop nationwide inventories of enteric emissions from the countries’ animal production industries. It has also been used by Italy to measure carbon dioxide emissions. ARS scientists also have designed another new technology to evaluate trace-gas emissions from confined animal production systems called the modified integrated horizontal flux (MIHF) technology. ARS and Agriculture and Agri-Food Canada evaluated this technique for global change and other trace-gases emitted from animal production systems. The MMD technique was the first truly non-invasive methodology for measuring methane emissions from animals under natural conditions. Results from these non-invasive studies have shown previous measurements using calorimeter chambers to be relatively insensitive to feedstuffs quality and animal activity, suggesting that current world animal-emission estimates generally based on calorimetric measurements can be improved. ARS scientists have cooperated with colleagues from the University of Alberta, Alberta, Canada, to develop the backward Lagrangian stochastic (bLS) analysis technique. This technique has been used to determine trace-gas emissions from lagoons using open-path laser spectrometers measuring concentrations directly over the lagoon surface. Emissions determined by the bLS technique compared well to other classical non-interference measurement techniques. The bLS technique has also been used to determine emissions from whole farm systems, including buildings and adjacent lagoons, by taking long-path concentration measurements downwind of the structures. A further use of this technique has been to evaluate ammonia and methane emissions from a large (one mile square) beef feedlot and a nearby retention pond. Open-path laser spectrometers were used to obtain concentrations at the lagoon and two places within and downwind of the feedlot. Emissions determined from the different locations were the same and both compared well with flux-gradient emissions determined nearby in the feedlot. The technique determined 15-min emissions thus allowing effects of management and animal activity to be observed, such as the result of animal urination on ammonia emissions and enteric emissions from ruminating periods on methane emissions. The use of the MMD technique served as a basis for establishing guidelines for Australia's efforts to reduce global GHG from their large animal industry. An ARS scientist was asked to coauthor the report to the Australia National Greenhouse Gas Inventory Committee on verification of greenhouse gas emissions from Australia. The MIHF technique is currently in use to develop Canada's global change emissions inventory and to evaluate best management practices by which Canadian agriculture will reduce its global change emissions. The bLS technique has the potential to be a significant new technology for accurately evaluating emissions from whole farms and individual components on a farms. The new methodologies have provided major advances in measurement technologies for evaluating global warming and air-quality gas emissions under both natural and agricultural systems. Development and application of micrometeorological methods will allow area-integrating, scale-appropriate, non-interfering assessment of ammonia and other trace-gas emissions from large CAFOs.

Harper, L. A., Sharpe, R. R., Parkin, T.B., De Visscher, A., van Cleemput, O., and Byers, F.M. 2004. Nitrogen cycling in swine production systems: Ammonia, nitrous oxide, and dinitrogen gas emissions. *J. Environ. Qual.* 33: 1189-1201 .

Desjardins, R., Denmead, O.T., and Harper, L.A. 2004. Evaluation of a micrometeorological mass balance method employing open-path lasers for measuring methane emissions from on-farm animal operations. *J. Environ. Qual.* (in press).

- **Methane and** N_2O **Emissions**. A study was conducted to compare the effects of different land use patterns on methane emission. One of the treatments evaluated in this study was a land surface covered with broadcast swine manure. The mean methane flux for cultivated corn/soybean systems receiving liquid swine manure in a year ranked in the 100th percentile for annual rainfall (1436 mm), was 0.16 g methane/m2/y. In a more typical year with respect to rainfall, mean methane flux from the same fields was 0.06 g methane/m2/y. Cultivated corn/soybean fields not receiving liquid swine manure had mean methane fluxes of 0.13 and - 0.06 g methane/m2/y in the wet and normal year, respectively. Increased methane fluxes observed in the swine manure-amended fields usually occurred soon after manure application, and it is hypothesized that a majority of the increased methane flux was due to out-gassing of dissolved methane in the liquid swine manure. It was found that landfills and swine manured fields were net emitters of methane over the two years of the measurement period. Differences between the two years of the study were due to differences in rainfall. It was estimated that the net methane flux for Iowa was 139,000 Mg per year. Soil emissions of N_2O, CO_2, and CH_4 were measured (mostly during the growing season) from 1999 to 2001 on irrigated and rainfed sites cropped to continuous corn. The soils in both sites were treated annually with beef feedlot manure, swine manure (rainfed only), N-fertilizer, and no-treatment check since 1998. In the irrigated site, growing season N_2O flux in 1999 was 38.4 g N ha^{-1} d^{-1} higher in the fertilizer (anhydrous ammonia) than the cattle manure, and cattle manure was 18.8 g N ha^{-1} d^{-1} higher than the check (8.6 g N ha^{-1} d^{-1}). In the 2000 growing season, N_2O flux of the fertilizer treatment was 28.9 g N ha^{-1} d^{-1} higher than the cattle manure and cattle manure was 42.9 g N ha^{-1} d^{-1} higher than the check (11.8 g N ha^{-1} d^{-1}). In the rainfed site, N_2O flux was similar among treatments except within 10 d after manure and N fertilizer applications when the effects of manure and N fertilizer were in the order: 119 g N ha^{-1} d^{-1} for swine manure, 71 for fertilizer, 43 for cattle manure, and 35 for the control treatment. This information provides direct evidence of the amount of methane and nitrous oxide that can be released from agricultural systems. These data can be used to help develop improved inventories of greenhouse gas emissions from land surfaces. These data can help policymakers understand the dynamics of greenhouse gas emissions from different systems and indicate potential mitigation strategies.

Eghball, B., D. Ginting, C. A. Shapiro, J. S. Schepers, and C. J. Bauer. 2002. Manure as carbon source for soil improvement and crop production: Site-specific application. In A. J. Schlegel (ed.) *Proceedings of the Great Plains Soil Fertility Conference* 9: 22-28.

Ginting, D., A. Kessavalou, B. Eghball, and J. W. Doran. 2003. Greenhouse gas emissions and soil indicators four years after manure and compost applications. *J. Environ. Qual*. 32: 23-32.

- **Effect of tillage and dairy manure on emissions at landscape level.** Dairy manure was applied each fall with conventional or conservation tillage on a corn/cotton rotation. Trace gas measurements were taken to determine whether these strategies could reduce GHG emissions. Dairy manure, tillage and landscape position did not significantly influence methane-C fluxes as shown by results for spring 2004, while CO_2-C flux varied with season. Conservation tillage increased CO_2-C fluxes compared to conventional tillage during the winter seasons. Effect of treatment (tillage and manure application) on N_2O flux was influenced by interactions between treatment and landscape position as well as treatment and season. During spring 2004, conservation tillage with dairy manure application resulted in a 55% decrease in N_2O flux compared to conventional tillage with manure application. On a drainageway landscape, animal manure application reduced N_2O flux by 70% and 46% with conventional and conservation tillage respectively. Adoption of conservation tillage and dairy manure has potential to reduce N_2O fluxes under similar farming systems and environmental conditions.

Topic: Rangelands, Pastures and Wetlands

Goals: Develop management practices that limit trace gas emissions while maintaining productive use of grasslands; quantify the relationship between soil C storage and trace gas flux; provide information to improve national trace gas inventories; quantify the role of buffer and riparian zones on trace gas exchange; quantify the impact of increasing CO_2 concentrations on trace gas exchange within rangeland ecosystems.

Projected Impact: Decreased greenhouse gas emissions without adverse effects on range and pasture lands.

Summary: Elevated atmospheric CO_2 levels change the composition of forage species in short-grass steppe systems and changes also impact forage quality. Management of semiarid lands influenced oxidation of methane. Overall, semiarid grasslands were observed to be sinks of atmospheric methane; however, grazing reduced the strength of the methane sink due to increased soil compaction.

Selected Accomplishments

- **Role of rangelands in mitigating land-atmosphere GHG emissions.** Field experiments in semi-arid rangelands in which management (grazing) and/or environment (CO_2) were manipulated were used to evaluate the responses of trace gas fluxes of plants and soils. Generally, dry conditions in grasslands of the Northern Great Plains led to small annual emissions of CO_2, while wetter years led to its assimilation. Recommended grazing practices appear to have only small effects on rates of annual CO_2 assimilation in the Colorado shortgrass steppe compared to the non-grazed or moderately heavy grazing. However, the emission of GHG from Wyoming sagebrush steppe may increase with cheatgrass invasion due to fundamental changes in nutrient cycling. Continued rising atmospheric CO_2 is likely to have only small consequences on the net exchange of GHG, mostly due to changes of soil water. The collective results of this work suggest that land-atmosphere exchange of GHG in semi-arid rangelands will be influenced in large part to the extent that soil water is affected by climate change, and that management within the constraints of recommended, sustainable practices may not have large effects on GHG exchange.

  Gilmanov, T. G., L. L. Tieszen, B. K. Wylie, L. B. Flanagan, A. B. Frank, M. R. Haferkamp, T. P. Meyers, and J. A. Morgan. 2005. Integration of CO_2 Flux and Remotely Sensed Data for Primary Production and Ecosystem Respiration Analyses in the Northern Great Plains: Potential for Quantitative Spatial Extrapolation. *Global Ecology and Biogeography* 14:271-292.

  LeCain, D. R., J. A. Morgan, G. S. Schuman, J. D. Reeder, and R. H. Hart. 2002. Carbon Exchange Rates and Species Composition of Grazed Pastures and Exclosures in the Shortgrass Steppe of Colorado. *Agriculture, Ecosystems and Environment* 93:421-435.

  Liebig, M. A., J. A. Morgan, S. J. Reeder, B. H. Ellert, H. T. Gollany, and G. E. Schuman. 2005. Greenhouse Gas Contributions and Mitigation Potential of Agricultural Practices in Northwestern USA and Western Canada. *Soil & Tillage Research* 83:25-52.

  Mosier, A. R., J. A. Morgan, J. Y. King, D. LeCain, and D. G. Milchunas. 2002. Soil-Atmosphere Exchange of CH_4, CO_2, NO_x, and N_2O in the Colorado Shortgrass Steppe Under Elevated CO_2. *Plant and Soil* 240:201-211.

  Mosier, A. R., E. Pendall, and J. A. Morgan. 2003. Soil-Atmosphere Exchange of CH_4, CO_2, NO_x, and N_2O in the Colorado Shortgrass Steppe Following Five Years of Elevated CO_2 and N Fertilization. *Atmospheric Chemistry and Physics Discussions* 3:2691-2706.

  Norton, U., A. R. Mosier, J. A. Morgan, J. D. Derner, L. J. Ingram, and P. Stahl. Trace Gas Emissions and Soil C and N Dynamics Following Moisture Pulses in Native Grass and Cheatgrass-Dominated Sagebrush Grasslands. *Soil Biology and Biochemistry* (in press)

  Parton, W. J., J. A. Morgan, W. Guiming, and S. J. Del Grosso. 2007. Projected Ecosystem Impact of the Prairie Heating and CO_2 Enrichment Experiment. *New Phytologist* 174:823-834.

  Pendall, E., S. Del Grosso, J. Y. King, D. R. LeCain, D. G. Milchunas, J. A. Morgan, A. R. Mosier, D. S. Ojima, W. A. Parton, P. P. Tans, and J. W. C. White. 2003. Elevated Atmospheric CO_2 Effects and Soil Water Feedbacks on Soil Respiration Components in a Colorado Grassland. *Global Biogeochemical Cycles* 17:1-13.

  Pendall, E., J. Y. King, A. R. Mosier, J. Morgan, and D. Milchunas. 2005. Stable Isotope Constraints on Net Ecosystem Production Under Elevated CO_2, pp. 182-198. In Flanagan, L. B., Ehleringer, J. R., and Pataki, D. E. (eds.) *Stable Isotopes and Biosphere-Atmospheric Interactions: Processes and Biological Controls.* Elsevier Inc., San Diego, CA. Book Chapter.

  Wylie, B. K., E. A. Fosnight, T. G. Gilmanov, A. B. Frank, J. A. Morgan, M. R. Haferkamp, and T. P. Meyers. 2007. Adaptive Data-Driven Models for Estimating Carbon Fluxes in the Northern Great Plains. *Remote Sensing of Environment* 106:399-413.

- **Impact of elevated CO_2 on the short-grass ecosystem.** Data was obtained concerning plant-water relations under elevated CO_2 that included the impacts upon species composition changes and reduced forage digestibility that could be expected with increasing atmospheric levels of CO_2.

Data are applicable to major areas of western US grazing lands as well as many regions of shortgrass steppe throughout the world.

Milchunas, D.G., A.R. Mosier, J.A. Morgan, D.R. LeCain, J.Y. King and J.Y. Nelson. 2005. Root production and tissue quality in a shortgrass steppe exposed to elevated CO_2: Using a new ingrowth method. *Plant and Soil* 268:111-122.

Pendell, E., A.R. Mosier, and J.A. Morgan. 2004. Rhizodeposition stimulated by elevated CO_2 in a semi-arid grassland. *New Phytologist* 162:447-458.

Nelson, J.A., J.A. Morgan, D.R. LeCain, A.R. Mosier, D.G. Milchunas and W.J. Parton. Parton, W.A. 2004. Elevated CO_2 increases soil moisture and Enhances plant water relations in a long-term field study in the semi-arid shortgrass steppe of Colorado. *Plant and Soil* 259:169-179.

Morgan, J.A., D.E. Pataki, C. Korner, H. Clark, H., S.J. Del Grosso, J. Grunzweig, A. Knapp, A.R. Mosier, P. Newton, and P. Niklaus. 2004. Water relations in grassland and desert ecosystem responses to elevated atmospheric CO_2. *Oecologia* 140:11-25.

Morgan, J.A., D.E. Pataki, C. Korner, H. Clark, S.J. Del Grosso, J. Grunzweig, J., A. Knapp, A.R. Mosier, P. Newton, and P. Niklaus, P. 2004. Water relations in grassland and desert ecosystem responses to elevated atmospheric CO_2. *Oecologia*. 140:11-25

Milchunas, D.G., A.R. Mosier, J.A. Morgan, D.R. LeCain, J.Y. King, and J.A. Nelson. 2004. Root production and tissue quality in a shortgrass steppe exposed to elevated CO_2 : Using a new in growth method. *Plant Soil*. 268: 111-122.

Morgan, J.A., A.R. Mosier, D.G. Milchunas, D.R. LeCain, J.A. Nelson, and W.J. Parton. 2003. CO_2 enhances productivity of the shortgrass steppe, alters species composition and reduced forage digestibility. *Ecological Applications*. 14:208-219.

Ferretti, D.F., E. Pendall, J.A. Morgan, J.A. Nelson, D.R. LeCain, and A.R. Mosier. 2003. Partitioning evapotranspiration fluxes from a Colorado grassland using stable isotopes: seasonal variations and implications for elevated atmospheric CO_2. *Plant and Soil Journal* 254:291-303.

LeCain, D.R., Morgan, J.A., Mosier, A.R., Nelson, J.A. 2003. Soil and plant water relations, not photosynthetic pathway, primarily influence photosynthetic responses in a semi-arid ecosystem under elevated CO_2. *Annals of Botany*. 92:41-52.

Mosier, A.R., J.A. Morgan, J.Y. King, D. LeCain and D.G. Milchunas. 2002. Soil-atmosphere exchange of CH_4, CO_2, NO_x and N_2O in the Colorado shortgrass steppe under elevated CO_2. *Plant and Soi*l. 2002. v. 240 p. 201-211.

- **Semi-arid soils a strong sink for atmospheric methane.** The mechanisms of trace GHG cycling in rangeland soils is unclear, as is its potential importance to global change. Research has documented that semi-arid soils are an important consumer of atmospheric trace gases and indicated that infiltrated water, which is vital in supporting microbial activity and in turn, is responsible for the consumption of atmospheric methane, is reduced by grazing. Grazing also appears to reduce microbial consumption of methane in semi-arid soils due to compaction. The semi-arid soils were determined to be a strong sink for atmospheric methane, which has not been reported in literature, but would affect the accuracy of global climate modeling. Management of semi-arid soils may thus be important in maximizing the sink for atmospheric trace gases.

McLain, J.E.T., Martens, D.A. 2004. Nitrous oxide flux from soil amino acid mineralization. *Soil Biology & Biochem*. 37:289-299.

McLain, J.E., Martens, D.A. 2006. N2O production by heterotrophic N transformation in a semi-arid soil. *Applied Soil Ecology*. 2006. 32(253-263).

McLain, J.E.T., Martens, D.A. 2006. Moisture Controls on Trace Gas Fluxes in Semiarid Riparian Soils. *Soil Sci Soc Am J* 70:367-377.

Martens, D.A., Emmerich, W.E., McLain, J.E., Johnsen, T.N., Jr. 2005. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. *Soil and Tillage Res*. 83:95-119.

- **GHG emissions from Riparian Buffers**: Riparian buffers are used throughout the world for the protection of water bodies from nonpoint source pollution, particularly N. Yet this water quality protection has the potential to cause air quality degradation from the production of nitrous oxide. We discovered that soil C/N ratios of >25 reduced the potential for nitrous oxide production. We initiated photoacoustic measurements of the actual nitrous oxide emission vs. soil carbon/nitrogen (C/N) ratios to determine if the soil C/N was an easily measured and widely applicable parameter for identification of hot spots of actual nitrous oxide emissions from riparian buffers. Initial results suggest that the actual emissions may be lower than the potential nitrous oxide production.

Component III: Agricultural Ecosystem Impacts

Topic: Cropping Systems

Goals: Measure and predict above and below-ground plant responses to multiple interactions of abiotic and biotic stresses with rising CO_2; develop physiological criteria for improving crop quality (including leaf/forage/residue quality) of plants grown under elevated CO_2; determine the causes for seed yield and quality decreases with increasing temperature; develop guidance for genetic modifications for improving yields.

Projected Impact: More sustainable crop production systems.

Summary: Research on responses of cropping systems to elevated CO_2 and other stresses has better quantified direct effects of CO_2 and interactive effects of CO_2 with other variables on crop growth, water use, yield, and product quality, and has improved our ability to predict these responses. It has identified selection and management strategies which could aid in adapting crops and cropping systems to global environmental changes and mitigate some of the negative impacts of those changes.

Selected Accomplishments

- **Elevated atmospheric CO_2 and N fertilization of grain sorghum and soybeans**. This work examined the effects of N application on CO_2 responses of soybean and grain sorghum using open top field chambers. Doubled CO_2 increased biomass in all 3 years for both grain sorghum and soybean. With soybean, while no impact on the plant C:N ratio was observed, total N content increased (average 29%) due to increased atmospheric N fixation with elevated CO_2. With grain sorghum, the total N uptake was unaffected, but C:N ratio was increased by elevated CO_2. CO_2 level did not affect the response to of grain sorghum to fertilizer N. The results from this study indicated that while elevated CO_2 may enhance crop production and change N status in plant tissue, changes of N fertilizer application may not be needed for sorghum.

  Torbert, H.A., S.A. Prior, H.H. Rogers, and G.B. Runion. 2004. Elevated Atmospheric CO2 Effects on N Fertilization in Grain Sorghum and Soybeans. *Field Crops Research* 88 (1):47-57.

- **Elevated atmospheric CO_2 effects on biomass production in conventional and conservation cropping systems**. This work compared responses to elevated CO_2 for conventional (tillage) vs. conservation (no-till) management grain sorghum and soybean rotations on a silt loam soil. The conservation system also used rotated winter cover crops of wheat, crimson clover and sunn hemp. Using the conservation system, cover crop residue was increased by doubled CO_2. Elevated CO_2 had a greater effect on increasing soybean residue than sorghum residue. Grain yield increases were also greater for soybean (46.1%) than for sorghum (10.0%) or wheat (22.6%) under high CO_2. Cumulative aboveground residue inputs were increased by elevated CO_2 in both conventional and no-till systems. Similarly, cumulative inputs were increased by conservation practices under both CO_2 treatments. Results suggest that residue inputs were increased with conservation management or elevated CO_2, with the greatest input occurring for a combination of these treatments.

Prior, S.A., G.B. Runion, H.A. Torbert, H.H. Rogers, and D.W. Reeves. 2005. Elevated Atmospheric CO2 Effects on Biomass Production and Soil Carbon in Conventional and Conservation Cropping Systems. *Global Change Biology* 11:657-665.

- **Elevated atmospheric CO_2 effects on crop nutrient dynamics under no-till conditions.** Increasing atmospheric CO_2 concentration could increase crop productivity and alter crop nutrient dynamics. Soybean and grain sorghum were grown for three years at ambient and twice ambient CO_2 under no-tillage. Macronutrient and micronutrient concentrations and contents were determined for grain, stover, and roots. Minirhizotrons were used to collect digital images of roots, to assay root growth and mortality. Although elevated CO_2 tended to reduce nutrient concentrations, high CO_2 consistently increased total nutrient content especially in grain tissue, primarily in soybean; this response pattern was more notable with macronutrients. This work indicates that fertilizer recommendations for given crops may need to be adjusted in the future when CO_2 concentrations are higher.

Prior, S.A., G.B. Runion, H.A. Torbert, and H.H. Rogers. 2007. Effects of Atmospheric CO2 Enrichment on Crop Nutrient Dynamics under No-Till Conditions. *Journal of Plant Nutrition*. (In press.)

Pritchard, S.G., S.A. Prior, H.H. Rogers, M.A. Davis, G.B. Runion, and T.W. Popham. 2006. Effects of Elevated Atmospheric CO2 on Root Dynamics and Productivity of Sorghum Grown under Conventional and Conservation Agricultural Management Practices. *Agriculture, Ecosystems & Environment* 113:175-183.

- **Potato root distribution and soil biology not affected by CO_2 level in the subarctic**. The effect of elevated atmospheric CO_2 concentration on fine root distribution and associated soil biological activity under subarctic conditions were assessed. Potatoes were grown in open top field chambers at three levels of CO_2 (ambient, ambient + 175 ppm, and ambient + 350 ppm) at Fairbanks, Alaska. Soil was cored to a depth of 60 cm and divided into four increments of 15-cm each for root length and mass determinations. The elevated CO_2 did not affect root growth, either root length density or mass at any depth or position. None of the soil biology variables examined were impacted by elevated CO_2.

Prior, S. A., G.B. Runion, H.H. Rogers, J.S. Conn, and V.L. Cochran. 2005. Atmospheric CO2 Enrichment of Potato in the Subarctic: Root Distribution and Soil Biology. *Environ. Control Biol.* 43 (3):165-172.

- **Changes in gene expression at elevated CO_2.** Determination, of which genes undergo changes in expression level in response to altered environmental conditions, and the consequences of such altered expression, helps identify targets for genetic manipulation to adapt crops to climate change. Over 30 genes whose expression changed (as measured by gene products) in the model plant *Arabidopsis thaliana* upon exposure to elevated CO_2 were identified, including some genes involved in plant defense and development. For maize, transcript levels of 387 genes changed by at least a factor of two in response to elevated CO_2. Some of these genes were involved in stomatal development and photosynthesis, but most had unidentified functions. Elevated CO_2 alters many plant processes in addition to photosynthesis and stomatal conductance, despite identification by some as the only targets responding to elevated CO_2.

Kim, S-H., Sicher R. C., Bae, H., Gitz, D. C., Baker, J. T., Timlin, D. J., Reddy, V. R. 2006. Canopy photosynthesis, evapotranspiration, leaf nitrogen, and transcription profiles of maize in response to CO2 enrichment. *Global Change Biology* 12: 588-600.

Bae, Hanhong and Sicher R. 2004. Changes of soluble protein expression and leaf metabolite levels in Arabidopsis thaliana grown in elevated atmospheric carbon dioxide. *Field Crops Research* 90: 61-73.

- **Models of stomatal conductance for predicting crop water use under global change conditions.** Partial stomatal closure at elevated carbon dioxide will affect crop water use and also affect climate itself as atmospheric CO_2 rises. The degree of closure varies greatly with species and other environmental conditions. Experimental observations were summarized as a set of models describing stomatal conductance for major crops. These models were then incorporated into soil-vegetation-atmosphere models to predict effects of rising atmospheric CO_2 on crop water use. The stomatal conductance models have also been used by others in GCMs to predict climate changes caused by rising atmospheric CO_2.

  Bunce, J. A. 2004. Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions. *Oecologia* 140: 1-10.

  Bunce, J. A. 2001. Direct and acclimatory responses of stomatal conductance to elevated carbon dioxide in four herbaceous crop species in the field. *Global Change Biology* 7: 323-331.

  Bunce, J. A. 2000. Responses of stomatal conductance to light, humidity and temperature in winter wheat and barley grown at three concentrations of carbon dioxide in the field. *Global Change Biology*. 6: 371-382.

- **Identified increased tillering and branching as leading to large crop yield increases under elevated CO_2.** Rising atmospheric CO_2 concentration represents an increase in a growth-limiting resource for many crop species. Crop varieties should be developed which are better able to utilize this resource, but identifying useful traits has been difficult. This work has shown that large intraspecific variation of yield response occurs in soybean and in wheat, such that increased branching or tillering in response to elevated carbon dioxide resulted in greater yield increases. However, the ability to increase branching or tillering at elevated carbon dioxide is often absent from modern germplasm for these species, indicating that breeding programs based only on elite modern cultivars may not include some of the traits most useful at future higher CO_2 levels.

  Ziska L. H., Morris, C. F. and Goins, E. W. 2004. Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: can yield sensitivity to carbon dioxide be a factor in wheat performance? *Global Change Biology* 10: 1810-1819.

  Ziska, L. H., Bunce, J. A. and Caulfield, F. A. 2001. Rising atmospheric carbon dioxide and seed yield of soybean genotypes. *Crop Science* 41: 385-391.

  Ziska, L. H. and Bunce, J. A. 2000. Sensitivity of field-grown soybean to future atmospheric CO2: selection for improved productivity in the 21st century. *Australian Journal of Plant Physiology* 27: 979-984.

- **Identified diverse causes of photosynthetic down-regulation with elevated CO_2.** An increase in photosynthesis is one of the key responses leading to increased plant growth with elevated carbon dioxide, but the initial stimulation often decreases during growth. Predicting the down-regulation of photosynthesis remains a major uncertainty for modeling crop growth under future climatic conditions. Diverse causes of down-regulation were found in various crop species: feedback inhibition caused by sugar accumulation, feedback inhibition caused by starch accumulation, premature senescence, greater sensitivity to midday water stress, and low leaf N content. These causes lead to a range of day to day and seasonal patterns of down-regulation of photosynthesis of various crop species. This information will improve the accuracy of crop simulation models when predicting crop responses to global change conditions.

  Bunce, J. A. and Sicher, R. C. 2003. Daily irradiance and feedback inhibition of photosynthesis at elevated carbon dioxide concentration in *Brassica oleracea*. *Photosynthetica* 41: 481-488.

  Bunce, J. A. and Sicher, R. C. 2001. Water stress and day-to-day variation in apparent photosynthetic acclimation of field-grown soybeans to elevated carbon dioxide concentration. *Photosynthetica* 39: 95-101.

Sicher, R. C. and Bunce, J. A. 2001. Adjustments of net photosynthesis in *Solanum tuberosum* in response to reciprocal changes in ambient and elevated growth CO 2 partial pressures. *Physiologia Plantarum* 112: 55-61.

Bunce, J. A. 2001. Seasonal patterns of photosynthetic response and acclimation to elevated carbon dioxide in field-grown strawberry. *Photosynthesis Research* 68: 237-245.

- **Limitations to the CO_2 productivity enhancement response**. A CO_2 enhancement ratio (ER) >1 suggests that CO_2 per se is limiting productivity or is alleviating another condition that is doing so. Projections of elevated CO_2 effects on agricultural productivity must account for both of these situations. Co-occurring stresses that may be alleviated by elevated CO_2 include pollutant O_3 and water stress. For example, in studies with seven different crops, ERs were highest when elevated CO_2 ameliorated the effects of O_3 by reducing stomatal conductance and entry into the leaves. Nutrient limitations, rising temperature and competition may act to restrict the ER to ≤1. A study with rice demonstrated that ER was <1 when elevated CO_2 accelerated development into a window of ambient T > 35 C that caused floral abortion and reduced seed yield. In one year of the rice study, total biomass production was limited by nutrient availability and in the other year by CO_2. The highest ERs were obtained at the lowest planting density. Comparisons between pot-grown and field-grown soybean demonstrated that there were no significant differences in the ER at twice-ambient CO_2 concentrations. To realize the full productivity benefit from increased CO_2, it will be necessary to manage environmental stresses and cultural practices that otherwise limit seed yields and biomass production.

Fiscus, E.L., J.E. Miller, F.L. Booker, A.S. Heagle and C.D. Reid. 2002. The impact of ozone and other limitations on the crop productivity response to CO_2. *Technology* 8:181-192.

Booker, F.L., J.E. Miller, E.L. Fiscus, W.A. Pursley and L.A. Stefanski. 2005. Comparative responses of container- versus ground-grown soybean to elevated CO_2 and O_3. *Crop Science* 45:883-895.

Booker, F.L. and E.L. Fiscus. 2005. The role of ozone flux in the suppression of ozone injury by elevated carbon dioxide in soybean. *Journal of Experimental Botany* 56:2139-2151.

Dubois, J.-J.B., EL Fiscus, FL Booker, MD Flowers and CD Reid. 2007. Optimizing the statistical estimation of the parameters of the Farquhar-von Caemmerer-Berry model of photosynthesis. *New Phytologist* 176:402-414. (Computer program available in Supplementary Material.)

Fiscus, EL, FL Booker, J-JB Dubois, TR Rufty, JW Burton and WA Pursley. 2007. CO_2 enhancement effects in container- versus ground-grown soybeans at equal planting densities. *Crop Science* 47:2486-2494.

Reid, CD and EL Fiscus. 2008. Ozone and density affect the response of biomass and seed yield to elevated CO_2 in rice. *Global Change Biology*. 14:60-76.

- **Rising CO_2 levels and food quality.** Effects of atmospheric CO2 increases on crop yield have been quantified for several crops, however, less is known regarding the impact of rising CO_2 on crop quality aspects. It was found that elevated CO_2 can have negative effects on the protein content of cereals such as wheat, but may have a positive influence on antioxidant levels in strawberry and the ratio of omega-3 relative to omega-6 fatty acids in mungbean, an important source of fatty acids in the human diet. Rising atmospheric CO_2 may also significantly affect food quality with subsequent effects on the health of American consumers. Lower concentrations of N, P, and Zn were found in potato tubers of two cultivars at elevated CO_2. Higher atmospheric CO_2 altered the lipid composition of soybean and peanut seed oil primarily through changes in the level of fatty acid saturation that may also significantly affect food quality with subsequent effects on the health of American consumers.

Burkey, K.O., Booker, F.L., Pursley, W.A., Heagle, A.S. 2007. Elevated carbon dioxide and ozone effects on peanut: II. Seed yield and quality. *Crop Science* 47: 1488-1497.

Fiscus, E.L., Booker, F.L., Dubois, J.-J. B., Rufty, T.W., Burton, J.W., Pursley, W.A. Carbon dioxide enhancement effects in container- versus ground-grown soybean at equal planting densities**.** *Crop Science* 47: 2486-2494.

Heagle, A.S., J.E. Miller, W.A. Pursley. 2003. Growth and yield responses of potato to mixtures of carbon dioxide and ozone. *Journal of Environmental Quality* 32:1603-1610.

Wang, S. Y., Bunce, J. A., Maas, J. L. 2003. Elevated carbon dioxide increases contents of antioxidant compounds in field-grown strawberries. *Journal of Agricultural and Food Chemistry* 51: 4315-1320.

Ziska, L. H., Palowsky, R., Reed, D. R. 2007. A quantitative and qualitative assessment of mung bean (*Vigna mungo* (L.) Wilczek) seed in response to elevated atmospheric carbon dioxide: potential changes in fatty acid composition. *Journal of the Science of Food and Agriculture* 87:920-923.

Wang, S. Y., Bunce, J. A. 2004. Elevated carbon dioxide affects fruit flavor in field-grown strawberries (*Fragaria x ananassa* Duch). *Journal of the Science of Food and Agriculture* 84: 1464-1468.

Ziska, L. H., Morris, C. F., Goins, E. F. 2004. Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: can yield sensitivity to carbon dioxide be a factor in wheat performance? *Global Change Biology* 10:1810-1819.

Wang, S. Y., Bunce, J. A., Maas, J. L. 2003. Elevated carbon dioxide increases contents of antioxidant compounds in field-grown strawberries. *Journal of Agricultural and Food Chemistry* 51: 4315-1320.

Ziska, L. H., Palowsky, R., Reed, D.R. 2007. A quantitative and qualitative assessment of mung bean (Vigna mungo (L.) Wilczek) seed in response to elevated atmospheric carbon dioxide: potential changes in fatty acid composition. *Journal of the Science of Food and Agriculture* 87:920-923.

- **Elevated CO_2 does not stimulate C_4 photosynthesis directly, but impacts water relations in Maize (*Zea mays*) grown for FACE experiments.** The mechanism of CO_2 effects on C_4 plants remains poorly understood. A rainfed-field experiment utilizing FACE technology was undertaken to determine the effects of elevated CO_2 on *Zea mays*. With an absence of water stress, there was no CO_2 effect on photosynthesis, carbon metabolism, growth or yield. Nevertheless, elevated CO_2 reduced stomatal conductance, transpiration and soil moisture depletion. During episodic dry periods, photosynthesis was greater under elevated CO_2. These results suggest that elevated CO_2 significantly enhances maize yield only when the crop is subjected to moderate to severe drought.

Leakey, A.B., M. Uribelarrea, E.A. Ainsworth, S.L. Naidu, A. Rogers, S.P. Long, and D.R. Ort. 2006. Photosynthesis, productivity and yield of maize are not affected by open-air elevation of CO2 concentration in the absence of drought. *Plant Physiology*. 140: 779-790.

Leakey, A.D., C.J. Bernacchi, F.G. Dohleman, and D.R. Ort. 2004. Will photosynthesis of maize (*Zea mays*) in the U.S. corn belt increase in future [CO2] rich atmospheres? An analysis of diurnal courses of CO2 uptake under free-air concentration enrichment (FACE). *Global Change Biology* 10: 951-962.

- **Global atmospheric changes alter the water balance of crop ecosystems.** Increasing atmospheric CO_2 and O_3 concentrations are likely to cause partial stomatal closure and would thus reduce water loss from leaves. However, the overall consequences for total plant water requirements are much less certain. Experiments with open-field-grown soybean showed that soybean canopy temperatures will likely increase about 0.5º C at midday and that evapotranspiration will be reduced from 9% to 16% at the elevated CO_2 concentrations expected for 2050. Such increases of canopy temperature may shift the geographic locations for optimal soybean production in the future, while the reductions in evapotranspiration may enable soybean to conserve some soil moisture and grow somewhat further into a drought cycle.

Bernacchi, C.J., B.A. Kimball, D.R. Quarles, S.P. Long, and D.R. Ort. 2007. Decreases in stomatal conductance of soybean under open-air elevation of [CO_2] are closely coupled with decreases in ecosystem evapotranspiration. *Plant Physiology*. 143: 134-144.

Bernacchi, C.J., A.D.B. Leakey, L.E. Heady, P.B. Morgan, F.G. Dohleman, J.M. McGrath, K.M. Gillespie, V.E. Wittig, A. Rogers, S.P. Long, and D.R. Ort. 2006. Hourly and seasonal variation in photosynthesis and stomatal conductance of soybean grown at future CO_2 and ozone concentrations for three years under fully open air conditions. *Plant Cell and Environment*. 29: 2077-2090.

Leakey, A.D. B., C. J. Bernacchi, D.R. Ort, and S.P. Long. 2006. Growth of soybean under free-air [CO_2] enrichment (FACE) does not cause stomatal acclimation. ***Plant Cell and Environment.*** 29:1794-1800.

Booker, F.L., E.L. Fiscus, and J.E. Miller. 2004. Combined effects of elevated atmospheric carbon dioxide and ozone on soybean whole-plant water use. *Environmental Management*. 33:S355-S362.

- **Elevated CO_2 alters soybean C and N dynamics**. The impact of elevated CO_2 on the ability of our major food crops to assimilate C and N will largely determine future yield potential. Using a FACE facility, C and N assimilation was investigated in soybeans grown under conditions forecast for 2050. Elevated CO_2 increased photosynthetic C assimilation, N fixation and respiratory C metabolism. However, increases of C uptake were less than predicted. The results suggest that there are unrecognized genetic limitations restricting the response of soybean to CO_2.

Rogers, A., D.J. Allen, P.A. Davey, P.B. Morgan, E.A. Ainsworth, C.J. Bernacchi, G. Cornic, O. Dermody, E.A. Heaton, J. Mahoney, X. Zhu, E.H. Delucia, D.R. Ort, and S.P. Long. 2004. Leaf photosynthesis and carbohydrate dynamics of soybeans grown throughout their life-cycle under free-air carbon dioxide enrichment. *Plant Cell and Environment*. 27: 449-458.

Rogers, A., Y. Gibon, P.B. Morgan, C.J. Bernacchi, D.R. Ort, and S.P. Long. 2006. Increased carbon availability at elevated carbon dioxide concentration improves nitrogen assimilation in legumes. ***Plant Cell and Environment.*** 29:1651-1658.

Ainsworth, E.A., A. Rogers, L.O. Vodkin, A. Walter, and U. Schurr. 2006. The effects of elevated [CO2] on soybean gene expression. An analysis of growing and mature leaves. *Plant Physiology*. 142:135-147.

Ainsworth E.A., A. Rogers, A.D.B. Leakey, L.E. Heady, Y. Gibon, M. Stitt and U. Schurr. 2007. Does elevated atmospheric [CO2] alter diurnal C uptake and the balance of C and N metabolites in growing and fully expanded soybean leaves? *Journal of Experimental Botany* 58, 579-591.

- **Selecting for CO_2 responsiveness and crop productivity.** It is generally assumed that today's crops are well suited to present-day high CO_2 levels, and well adapted to future levels because crops have been bred under steadily increasing levels of atmospheric CO_2. This assumption has never been tested. To test it, we grew oat (*Avena sativa*) cultivars that had been released early and late in the 20th century, in CO_2 concentrations representative of the 1920s, current levels, and a projected future concentration for the middle of this century, (300, 400 and 500 parts per million, respectively). Newer lines were less responsive than older lines to rising CO_2 as indicated by leaf area and tiller number. Newer lines were also less variable in their response to CO_2 than were older lines, and the most responsive lines were found among older cultivars. For oat, newer lines are not intrinsically more responsive to rising CO_2 levels than older lines, and phenotypic homogenization among modern lines could hamper efforts to identify desirable characteristics associated with CO_2 responsiveness.

L. H. Ziska and D. M. Blumenthal, 2007. Empirical Selection of Cultivated Oat in Response to Rising Atmospheric Carbon Dioxide. Crop Sci. 2007 47: 1547-1552.

- **Atmospheric CO_2 concentration and seed quality and germination**. The parental environment, typically considered as temperature, light, soil moisture, and nutrient availability, are all known to influence seed quality. Elevated atmospheric CO_2 is a condition of the parental environment that may also influence seed quality, yet is seldom evaluated. To measure the influence of elevated CO_2 on seed quality, a highly-diverse line of rust-resistant common wheat was grown in a glasshouse and six distinct types or "entries" were selected from the offspring. These were then grown under 350, 700, and 1000 ppm atmospheric CO_2. The resulting grain quality was analyzed and related to germinability. Germination was near 100% for all treatments but different patterns emerged among entries for germination rate. The C/N ratio was also similar among treatments but there was a negative correlation between C content and germination rate. Thus, elevated CO_2 can affect both seedling establishment through germination rate, and grain quality. The intra-population variations of the germination response found among the six entries suggest the response to elevated CO_2 can be addressed and should be considered in future breeding efforts.

Bai, Y., C.R. Tischler, D.T. Booth and E.M. Taylor. 2003. Variation in germination and grain quality within rust resistant common wheat germplasm as affected by parental $C0_2$ conditions. *Environmental and Experimental Botany*. 50:159-168.

- **Seed yields of crops are sensitive to increasing temperatures.** Seed yield of several important crops decrease at high temperatures while they usually increase with elevated CO_2. Experiments were conducted in controlled environment, sun-lit chambers to determine how changes in both factors affected seed yield. In rice, soybean, peanut, kidney bean, mung bean, and grain sorghum, yield decreased about 10% per degree above the optimum temperature for crop yield; that is seed yields typically decrease to zero at about 10 degrees C above the optimum temperature for crop yield. The main factors in reproductive process failure are decreased pollen production and viability, which lowers seed-set of all crops. However, some crops such as soybean, peanut, and kidney bean, experience a progressive decrease in seed size with increasing temperature. In general, there was no CO_2 by temperature interaction. A search has been conducted for cultivars of rice and soybean with a greater tolerance to high temperatures. One cultivar from India, N-22, was clearly the most heat tolerant of the cultivars investigated. High temperature tolerance in rice might be related to earlier time-of day of flowering (which avoids higher diurnal temperatures).

Jain M, Prasad PVV, Boote KJ, Allen LH, Chourey PS. 2007. Effects of season-long high temperature growth conditions on sugar-to-starch metabolism in developing microspores of grain sorghum (Sorghum bicolor L. Moench). *Planta*(online)DOI 10.1007/s00425-007-0595-y

Prasad PVV, Boote KJ, Allen LH. 2006. Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [Sorghum bicolor (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agricultural and Forest Meteorology* 139:237-251.

Prasad PVV, Boote KJ, Allen LH, Sheehy JE, Thomas JMG. 2006. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. *Field Crops Research* 95:398-411.

Prasad PVV, Boote KJ, Vu JCV, Allen LH. 2004. The carbohydrate metabolism enzymes sucrose-P synthase and ADG-pyrophosphorylase in phaseolus bean leaves are up-regulated at elevated growth carbon dioxide and temperature. *Plant Science* 166:1565-1573.

Thomas JMG, Boote KJ, Allen LH, et al. 2003. Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance. *Crop Science* 43:1548-1557.

Prasad PVV, Boote KJ, Allen LH, Thomas JMG. 2003. Super-optimal temperatures are detrimental to peanut (*Arachis hypogaea L.*) reproductive processes and yield at both ambient and elevated carbon dioxide. *Global Change Biology* 9:1775-1787.

Prasad PVV, Boote KJ, Allen LH, Thomas JMG. 2002. Effects of elevated temperature and carbon dioxide on seed-set and yield of kidney bean (*Phaseolus vulgaris L.*). *Global Change Biology* 8:710-721.

- **Leaf-atmosphere vapor pressure deficit influences plant growth response to temperature**. Prediction of the impacts of global climate change and interactions of environmental pollutants on plant growth is still not resolved due to a number of confounding interactions in the response to environmental variables such as temperature and leaf-atmospheric vapor pressure deficit (vpd). Using custom-built, Outdoor Plant Environmental Chambers (OPECs), we examined the interactive influence of vpd and temperature on the growth of tall fescue, a cool season grass. At a constant vpd, contrary to expectations, the growth of the grass markedly increased with temperature. Increasing vpd at a constant temperature, which is a common consequence of most temperature experiments, caused the growth to decrease. Assuming that vpd remains constant with global warming, as it has in the past, then growth of cool season species might be stimulated by temperature increases. However, most temperature studies do not control for vpd, and those results should be re-examined.

Flowers, M.D., E.L. Fiscus, K.O. Burkey, F.L. Booker, J.-J. B. Dubois. 2007. Photosynthesis, chlorophyll fluorescence, and yield of snap bean (Phaseolus vulgaris L.) genotypes differing in sensitivity to ozone. *Environmental and Experimental Botany* 61:190-198. (OPEC design reference).

Sinclair, T., E. Fiscus, B. Wherley, M. Durham, T. Rufty. 2007. Atmospheric vapor pressure deficit is critical in predicting growth response of "cool-season" grass Festuca arundinacea to temperature change. *Planta* 227:273-276.

- **Elevated atmospheric CO_2 improve wheat and sorghum plant water status and consequent photosynthetic rates and growth**. Rising atmospheric CO_2 concentration is predicted to cause warmer mean air temperatures and altered precipitation patterns, which could increase the likelihood of high temperature extremes and the occurrences of drought. To determine the interactive effects of atmospheric CO_2 concentration and soil-water content on plants, wheat and grain sorghum were grown under well-watered and dry soil moisture regimes, and at ambient and 200 ppm above ambient CO_2 concentrations. Elevated CO_2 caused higher leaf water potentials, and reduced stomatal conductances, while increasing net photosynthetic rates. Therefore, by ameliorating the adverse effects of drought, elevated atmospheric CO_2 improved the plant water status for both wheat and sorghum, which indirectly resulted in increased net daily and seasonal C gain for both crops.

Wall, G.W., T.J. Brooks, N.R. Adam, A.B. Cousins, B.A. Kimball, P.J. Pinter Jr., R.L. LaMorte, J.M. Triggs, M.J. Ottman, S.W. Leavitt, A.D. Matthias, D.G. Williams, and A.N. Webber. 2001. Elevated atmospheric CO2 improved sorghum plant water status by ameliorating the adverse effects of drought. *New Phytologist* 152:231-248.

Wall, G.W., R.L. Garcia, B.A. Kimball, D.J. Hunsaker, P.J. Pinter, Jr., S.P. Long, C.P. Osborne, D.L. Hendrix, F. Wechsung, G. Wechsung, S.W. Leavitt, R.L. LaMorte, and S.B. Idso. 2005. Interactive effects of elevated CO2 and drought on wheat. *Agronomy J*. 98:354-381.

Cousins, A.B., N.R. Adam, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., M.J. Ottman, S.W. Leavitt, and Webber A.N. 2003. Development of C4 photosynthesis in Sorghum leaves grown under free-air CO2 enrichment (FACE). *Journal of Experimental Botany* 54(389):1969-1975.

Cousins, A.B., N.R. Adam, G.W. Wall, B.A. Kimball, P.J. Pinter Jr., M.J. Ottman, S.W. Leavitt, and A.N. Webber. 2002. Photosystem II energy use, non-photochemical quenching and the xanthophyll cycle in Sorghum bicolor grown under drought and free-air CO2 enrichment (FACE) conditions. *Plant Cell and Environment*. 25:1551-1559.

- **Elevated CO_2 stimulates the growth of most crops under open-field conditions**. To determine the likely effects of increasing atmospheric CO_2 concentration on the productivity of crops under field conditions, FACE experiments have been conducted on wheat, perennial ryegrass, and rice, which are C_3 grasses; sorghum, a C_4 grass; white clover and soybean, C_3 forage and grain legumes, respectively; potato, a C_3 forb with tuber storage; and cotton and grape, which are C_3 woody perennials. Synthesizing information from numerous reports stemming from these experiments, elevated CO_2 increased photosynthesis, biomass, and yield substantially in C_3 species, but little in C_4. Woody perennials had larger growth responses to elevated CO_2 than herbaceous species. Growth stimulations were as large or larger under water-stress compared to well-watered conditions, whereas at low soil N, stimulations of non-legumes were reduced, while elevated CO_2 strongly stimulated the growth of the clover legume both at ample and low N conditions.

Kimball, B.A., Z. Jianguo, C. Lei, K. Kobayashi, and M. Bindi. 2002. Responses of agricultural crops to free-air CO2 enrichment. *Chinese Journal of Applied Ecology* 13(10): 1323-1338.

Kimball, B.A., K. Kobayashi, and M. Bindi. 2002. Responses of agricultural crops to free-air CO2 enrichment. *Advances in Agronomy* 77:293-368.

Kimball, B.A. 2006. The effects of free-air [CO2] enrichment of cotton, wheat, and sorghum. In J. Noesberger, S.P. Long, R.J. Norby, M. Stitt, G.R. Hendrey, and H. Blum (eds.), *Managed Ecosystems and CO2: Case Studies, Processes, and Perspectives*, Springer, Heidelberg, Germany. 47-70. (Book chapter).

Kimball, B.A. 2004. Global environmental change: implications for agricultural productivity. *Crop, Environment & Bioinformatics* 1:251-263.

Kimball, B.A. 2003. Response of plants to elevated atmospheric CO2. *Indian Journal of Plant Physiology* (Special Issue) 18-24.

- **Elevated CO_2 causes more of the C in sorghum residue to be in forms that decompose slowly.** Higher levels of CO_2 directly stimulate the growth of plants, and because larger plants have more roots and residue, there is a potential for storage of more carbon in the soil. Therefore, as part of FACE experiments, measurements of the effects of elevated CO_2 on the growth of sorghum were made, and in addition, the amounts of soil carbon were determined that went into forms that decay both quickly and slowly. On average, 53% of the SOC under elevated CO_2 was in the slow pool and 47% in the fast pool, compared to 46% and 54%, respectively, for the ambient CO_2 control plots. Most of change could be attributed to the new sorghum residue nearly doubling the amount carbon going to the slow pool compared to the fast pool. These results help to assess how much carbon can be sequestered in soils and thereby mitigate the rate of rise of atmospheric CO_2 concentration.

Cheng, L., S.W. Leavitt, B.A. Kimball, P.J. Pinter Jr, M.J. Ottman, A. Matthias, G.W. Wall, T. Brooks, D.G. Williams, and T.L. Thompson. 2007. Dynamics of labile and recalcitrant soil carbon pools in a sorghum Free-Air CO2 Enrichment (FACE) agroecosystem. *Soil Biology and Biochemistry.* 39: 2250-2263

- **Sour orange tree growth and fruit production highly responsive to elevated CO_2 in 17-year experiment.** The long-term responses of trees to elevated CO_2 are especially crucial to mitigating the rate of atmospheric CO_2 increase, and to determining the productivity of future agricultural tree crops. A long-term experiment with sour orange trees in open-top CO_2 enrichment chambers was started in Phoenix, AZ during 1987 and terminated during 2005. There was a productivity plateau at a 51 % enhancement of annual fruit and incremental wood production over the last several years of the experiment. When summed over the duration of the experiment, there was an overall enhancement of 70% of total biomass production. Thus increasing atmospheric CO_2 concentration should be highly beneficial to future citrus production. These data also indicate that trees can sequester significantly more carbon at higher CO_2 concentrations, which will help to mitigate the rate of rise of CO_2 concentration in the atmosphere. This was the longest continually running CO_2-enrichment ever conducted and as such has received numerous citations in the effort to elucidate what the likely effects of elevated CO_2 will have on forests and orchards in future. Impact is also indicated by invitations to present the work at a workshop of Southwest forest managers and an international conference in Japan. The research was funded by the Dept. of Energy during its early years, and the final massive harvest was funded by NRI.

Adam, N.R., G.W. Wall, B.A. Kimball, S.B. Idso, and A.N. Webber. 2004. Acclimation of photosynthesis in leaves of sour orange trees grown at elevated CO2 for 14 years. *New Phytologist* 163:341-347.

Leavitt, S.W., S.B. Idso, B.A. Kimball, J.M. Burns, A. Sinha, and L. Stott. 2003. The effect of long-term atmospheric CO2 enrichment on the intrinsic water-use efficiency of sour orange trees. *Chemosphere* 50:217-222.

Kimball, B.A., and S.B. Idso. 2005. Long-term effects of elevated CO2 on sour orange trees. In K. Omasa, I. Nouchi, and L.J. De Kok (eds.) *Plant Responses to Air Pollution and Global Change*, Springer-Verlag, Tokyo. 73-80. (Book chapter)

Kimball, B.A., S.B. Idso, S.M. Johnson, and M.C. Rillig. 2007. Seventeen years of CO2 enrichment of sour orange trees: Final results. *Global Change Biology* 13: 2171–2183).

- **Tissue composition and wood properties of sour orange trees little affected by 17-year exposure to elevated CO_2.** Whether or not the tissue composition and wood properties of trees will change with the increasing atmospheric concentrations of CO_2 is important for determining the future quality of citrus fruit, the engineering properties of lumber, and the pulping quality of wood fiber for paper. A long-term experiment was started in 1987 in Phoenix, AZ, with sour orange trees in open-top CO_2 enrichment chambers that lasted until 2005 when the trees were harvested. The 17-year exposure to elevated CO_2 resulted about a 5% increase vitamin C concentration of the fruit. There were no significant changes in the elemental composition of tissues, nor were there significant changes in mycorrhizal infections which could have affected nutrient uptake. There were small but statistically significant increases in wood basic specific gravity and in the number of rays per mm, but percentages of tissues, numbers of vessels per square mm, vessel diameters, fiber wall thicknesses, and moduli of elasticity were unaffected. These results suggest that the quality of future citrus fruit, the mechanical properties of lumber, and the pulping properties for paper will be minimally affected in the future by the increasing atmospheric CO_2 concentration. The research was funded by Dept. of Energy during its early years; and the final massive harvest, the elemental analyses, the mycorrhizal studies, and the determinations of wood properties were funded by the National Research Initiative of the Cooperative States Research Education and Extension Service.

Idso, S.B., B.A. Kimball, P.E. Shaw, W. Widmer, J.T. Vanderslice, D.J. Higgs, A. Montanari, and W.D. Clark. 2002. The effect of elevated atmospheric CO2 on the Vitamin C Concentration of (sour)orange juice. *Agriculture Ecosystems & Environment* 90(1):1-7.

Kimball, B.A., S.B. Idso, S.M. Johnson, and M.C. Rillig. 2007. Seventeen years of CO2 enrichment of sour orange trees: Final results. *Global Change Biology* 13: 2171–2183).

- **Photosynthesis of citrus acclimates at long-term elevated growth CO_2 and high temperature**. In a study with sweet orange, grown for 29 months under ambient and double-ambient CO_2 and at ambient and 6^{o}C above ambient temperatures, leaves of trees grown at elevated CO_2 have higher photosynthetic rate, lower transpiration and conductance, and greater water-use efficiency (WUE) than trees grown at ambient CO_2. Although WUE was reduced by high temperature, elevated growth CO_2 compensated for the adverse effect of high temperature on leaf WUE. The activity and protein concentration of Rubisco, the primary photosynthetic carboxylating enzyme, were down-regulated at elevated growth CO_2, but total leaf soluble protein level was not affected by elevated CO_2 and high temperature, and the contents of leaf soluble sugars and starch were higher under elevated CO_2 but unaffected by high temperature. This study illustrated that in the absence of other environmental stresses, citrus photosynthesis should perform well under future rising atmospheric CO_2 and temperature.

Vu, J.C.V., Newman, Y.C., Allen, L.H., Jr., Gallo-Meagher, M., Zhang, M-Q. 2002. Photosynthetic acclimation of young sweet orange trees to elevated growth CO_2 and temperature. *Journal of Plant Physiology* 159: 147-157.

- **Leaf photosynthesis of the C_4 sugarcane is enhanced by elevated growth CO_2 at an early leaf growth stage.** Leaf photosynthetic rates, activities of the C_4 photosynthetic and sucrose-metabolizing enzymes, and concentrations of chlorophyll, soluble protein and sucrose of sugarcane were all enhanced by double-ambient growth CO_2 at an early growth stage of the leaf. Leaves of the elevated CO_2-grown plants had lower stomatal conductance, less transpiration, and greater water-use efficiency throughout the growth and development of the leaf, and leaf area, above-ground plant biomass and volume of stem juice, determined at final harvest, were all enhanced by elevated CO_2. This work forms the basis for research to understand the increase in biomass and the photosynthetic acclimation and adaptation of C_4 crops in response to future rising atmospheric CO_2.

Vu, J.C.V., Allen, L.H., Jr., Gesch, R.W. 2006. Up-regulation of photosynthesis and sucrose metabolism enzymes in young expanding leaves of sugarcane under elevated growth CO_2. *Plant Science* 171: 123-131.

- **Crop growth models can simulate elevated CO_2 response**. To predict the likely effects of elevated CO_2 and any associated climate change on future productivity of wheat and sorghum, several wheat and crop growth simulation models (ecosys, AFRCWHEAT2, LINTULCC2, SIRIUS, APSIM-Nwheat) were tested against wheat and sorghum growth data obtained using FACE technology in open-field plots in Phoenix, AZ. The models have varying levels of detail in their handling of physiological processes, yet most model results were acceptably close to observed values, which greatly strengthen confidence in the use of such models for assessing future productivity.

Asseng, S., P.D. Jamieson, B.A. Kimball, P.J. Pinter Jr, K. Sayre, J.W. Bowden, and S.M. Howden. 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric C02. *Field Crops Research* 85:85-102.

Ewert, F., D. Rodriguez, P. Jamieson, M.A. Semenov, R.A.C. Mitchell, J. Goudriaan, J.R. Porter, B.A. Kimball, P.J. Pinter Jr., R. Manderscheid, H.J. Weigel, A. Fangmeier, E. Fereres, and F. Villalobos. 2002. Effects of elevated CO2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agriculture Ecosystems & the Environment* 93:249-266.

Grant, R.F., B.A. Kimball, G.W. Wall, J.M. Triggs, T.J. Brooks, P.J. Pinter, M.M. Conley, M.J. Ottman, R.L. Lamorte, S.W. Leavitt, T.J. Thompson, and A.D. Matthias. 2004. Modeling elevated carbon dioxide effects on water relations, water use, and growth of irrigated sorghum. *Agronomy Journal* 96: 1693-1705.

Manunta, P., R.F. Grant, Y. Feng, B.A. Kimball, Pinter Jr., P.J., R.L. LaMorte, D.J. Hunsaker, and G.W. Wall. 2002. Changes in mass and energy transfer between the canopy and the atmosphere: model development and testing with a free-air CO2 enrichment (FACE) experiment. *Journal of Biometeorology* 46: 9-21.

- **Rigorous standard procedures developed for assessing responses of crop models to temperature and soil N.** Crop simulation models are widely used to predict temperature and soil N effects on crop growth, development, and yield. However, the responses of individual processes in the models to temperature and N are often not examined critically. Two procedures were developed for assessing how models respond to environmental factors. The first approach covers major physiological processes in a balanced fashion, does not require access to source code, is easily interpretable by non-modelers, and is readily documented and employed with different models. It is based on the use of standardized data and presentation of outputs and does not require adjustments for specific crops or research questions. The second approach uses regression to assess how different treatments or environmental factors affect model performance. Both procedures provide the foundation for assessing modeled responses to temperature in a structured and reproducible fashion, thus leading to more robust models and ultimately, applications of models to problems such as global change.

White, J.W., G. Hoogenboom, and L.A. Hunt. 2005. A structured procedure for assessing how crop models respond to temperature. *Agronomy J*. 97:426-439.

White, J.W., K.J. Boote, G. Hoogenboom, and P.G. Jones. 2007. Regression-based evaluation of ecophysiological models. *Agronomy J*.. 99:419-427.

- **Inclusion of genetics information in crop growth models improves accuracy of predictions.** Incorporating genetic information into crop simulation models may strengthen model application to specific fields such as global change. Results with CSM-GeneGro, a gene-based model for common bean, demonstrated that this innovative approach can enhance the prediction of how global change will impact agricultural production. The improved model can be applied directly to research or management issues. Subsequent work with wheat and sorghum shows promise for applying the approach to other crops, however modelers and physiologists will have to be proactive in accessing information and tools being developed in the plant genomics community.

Hoogenboom, G., J.W. White, and C.D. Messina. 2004. From genome to crop: integration through simulation modeling. *Field Crops Research* 90:145-163.

White, J.W. 2006. From genome to wheat: Emerging opportunities for modeling wheat growth and development: Modeling Quality Traits and Their Genetic Variability for Wheat. *European Journal of Agronomy* 25:79-88.

- **Roles for genomics in global change research highlights need for collaborative research.** Global change processes present multiple challenges to agricultural productivity that can be met effectively by changing the crop environment through management, and by modifying the crop genome (the genotype or variety) through plant breeding and molecular biology. How the fields of plant genomics, plant breeding, physiology and agronomy can be better integrated to address issues related to global change was reviewed. Key findings including problems such as heat and drought tolerance showed where a continuous effort is needed to ensure that plants are studied under conditions relevant to field production, that field studies are managed to avoid extraneous variation (e.g., due to variable soil conditions or pest pressure) and that seemingly promising new traits are examined from a "whole plant" perspective that considers likely tradeoffs.

Edmeades, G.O., G.S. McMaster, J.W. White, and H. Campos. 2004. Genomics and the physiologist: bridging the gap between genes and crop response. *Field Crops Research* 90:5-18.

White, J. W., McMaster, Gregory S., and Edmeades, Greg O. 2004. Physiology, genomics and crop response to global change. *Field Crops Research* 90:1-3.

White, J. W., McMaster, Gregory S., and Edmeades, Greg O. 2004. Genomics and crop response to global change: what have we learned? *Field Crops Research* 90:165-169.

- **Technology for warming of experimental plots under open-field conditions**. A method for applying a heating treatment to open-field plant canopies is needed that will warm vegetation as expected by future climate. A theory of operation for infrared heaters was derived that enables performance and energy costs to be predicted. A control system was developed that maintains a constant degree of warming of a heated plot above that of a reference plot. Hexagonal arrays of the heaters tilted by 45 degrees at a height of 1.2 m above the crop canopy produced good uniformity of the warming treatment over 3m-diameter plots. This system provides a critically needed technology for *in situ* experiments addressing the interaction of increased temperature with other changing parameters associated with global change.

Kimball, B.A. 2005. Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* 11:2041-2056.

- **Scaling projected impacts of global change from plot level to regional or continental scales.** To obtain meaningful projections of impacts of global change, plot-level studies must be scaled-up. Two approaches show promise. Linking simulation models to climate data has resulted in successful simulation of wheat yield across the US, and further work is underway to develop requisite datasets documenting current cropping practices to be used as model inputs. A second approach being pursued for wheat involves use of agroclimatological analyses of interpolated climate surfaces to delimit megaenvironments, (MEs, defined as global regions that are not always geographically contiguous) – with similar adaptation patterns based on production factors, consumer preferences and wheat growth habits. Possible impacts of warming are represented through changes of regions assigned to different MEs or regions that become unsuitable for wheat. Wheat modeling was partially supported through funding from NASA.

Hodson, D.P., and J.W. White. 2007. Use of spatial analysis for global characterization of wheat-based production systems. *Journal of Agricultural Science* 145: 115-125.

- **Atmospheric CO_2, temperature and drought interact to affect soybean seed composition.** Soybeans are a major dietary source of alpha-tocopherol (vitamin E) and the main source of isoflavones, compounds with estrogenic activity. Alpha-tocopherol increased several fold in soybean seeds that developed at 28°C compared to those developed at 18°C, while isoflavones decreased more than 90% over the same range. In both cases, effects of elevated temperature were reduced in plants grown at levels of elevated atmospheric CO_2 expected by the end of this century. Temperature effects were confirmed in the field comparing seeds from hot, dry years to those from cool, moist ones. More recent experiments determined that 7-day heat "spells" or drought-simulating local weather elicited significant changes in seed composition when given midway through seed development. However, elevated CO_2 did not affect the response. Atmospheric CO_2 effects depend on interactions with environmental variables such as temperature and drought and the timing of exposure may be critical.

  Britz, S.J., D.F. Kremer. 2002. Warm temperatures or drought during seed maturation increase free α-tocopherol in seeds of soybean (Glycine max [L.] Merr.). *J. Agric. Food Chem*. 50: 6058-6063.

  Caldwell, C.R., S.J. Britz, and R.M. Mirecki. 2005. Effect of temperature, elevated carbon dioxide, and drought during seed development on the isoflavone content of dwarf soybean [Glycine max (L.) Merrill] grown in controlled environments. *J. Agric. Food Chem*. 53: 1125-1129.

- **Elevated growth temperature increases γ-Oryzanol in brown rice**. Rice is the most important crop in the world, but is currently widely grown near its maximum temperature. Temperature gradient greenhouses were used to compare the composition of rice seeds from lines grown at ambient or ambient + 4.5°C temperature treatments. In contrast to soybean, there was little effect of temperature on tocopherols and tocotrienols, although these compounds varied widely among the 6 rice lines investigated. γ-Oryzanol, a family of ferulated phytosterols with interesting potential as antioxidants and inhibitors of cholesterol uptake in humans, increased 30-40% at elevated temperature in 4 of 6 lines and most this change (60-80%) resulted from increases in 24-methylenecycloartanyl ferulate. The impact of changes in this compound on the temperature sensitivity of rice seeds and on human health needs further study.

  Britz, S.J., P.V.V. Prasad, R.A. Moreau, L. Hartwell Allen, Jr., D.F. Kremer, and K.J. Boote. 2007. Influence of growth temperature on the amounts of tocopherols, tocotrienols, and γ-oryzanol in brown rice. *J. Agric. Food Chem*. 55; 7559-7565.

- **Plant responses to UV radiation**. Solar ultraviolet radiation is an important environmental factor affecting plants, especially in regard to the amounts and types of flavonoids and phenolic acids produced in leaves that act as sunscreens. These compounds are believed to have beneficial dietary effects on cardiovascular health. Using a greenhouse system developed to screen large numbers of plants for sensitivity to UV radiation, 16 varieties of green and red leaf lettuce were identified on the basis of growth and accumulation of phenolics for further investigation. Additionally, plant growth depends on the ability to repair molecules damaged by UV. The inhibitory effect of solar UV radiation was enhanced in DNA repair-defective lines of Arabidopsis. Plants defective in the cyclobutane dimer photolyase were sensitive to UV-B, indicating that this enzyme plays an important role in UV resistance. A mutant defective in nucleotide excision repair also displayed sensitivity to solar UV-B, suggesting that either the transcription-coupled repair of UV-induced dimers, or the repair of some other UV-induced lesion, is also important. Overall, this research identified several important mechanisms involved in plant sensitivity to UV radiation.

  Grant: Effect of UV-B on Phytochemical Composition, S. Britz (PI), USDA-CSREES UV-B Monitoring and Effects Program, $25,000, 2002-2003.

Zhang, J., M.B. Satterfield, J.S. Brodbelt, S.J. Britz, B. Clevidence, and J.A. Novotny. 2003. Structural characterization and detection of kale flavonoids by electrospray ionization mass spectrometry. *Anal. Chem*. 75: 6401-6407.

Gitz, D.C., III, L. Liu-Gitz, S.J. Britz, and J.H. Sullivan. 2005. Ultraviolet-B effects on stomatal density, water-use efficiency, and stable carbon isotope discrimination in four glasshouse-grown soybean (Glyicine max) cultivars. ***Environ. Exptl. Bot.*** 53: 343-355.

Caldwell, C.R., and S.J. Britz. 2006. Effect of supplemental ultraviolet radiation on the carotenoid and chlorophyll composition of green house-grown leaf lettuce (Lactuca sativa L.) cultivars. ***J. Food Comp. Anal***. 19: 63.

Britt, A., and E.L. Fiscus. 2003. Growth responses of *Arabidopsis* DNA repair mutants to solar irradiation. ***Physiol. Plant.*** 118:183-192.

- **Atmospheric aerosols influence vegetative C assimilation**. Increasing atmospheric concentrations of aerosols could affect agricultural productivity and the global C cycle by changing the amount, scatter and spectral distribution of light plants receive. The daytime growing season CO_2 flux at six sites (forest, grasslands, and croplands) with collocated aerosol and surface radiation measurements were analyzed for light scatter, effect of cloud cover, and aerosol optical depths. Results indicated that aerosols exert a significant impact on net CO_2 exchange and their effect may be even more significant than that due to clouds. The CO_2 sink increased with aerosol loading for forest and crop lands, and decreased for grassland. Canopy architecture may be partly responsible for differences in response between vegetation types. In an experiment with soybean, plants grown under shelters covered by a light-diffusing material showed that biomass increased in the diffuse-light treatment due to better light interception within the canopy but seed yield was not affected. The potential of the vegetated land surface to be a sink for atmospheric C depends in part on regional aerosol loading, which needs to be considered in estimates of vegetation responses to future climate conditions.

Niyogi, D., H.-I. Chang, V.K. Saxena, T. Holt, K. Alapaty, F.L. Booker, F. Chen, K. J. Davis, B. Holben, T. Matsui, T. Meyers, W. C. Oechel, R. A. Pielke, Sr, R. Wells, K. Wilson, Y. Xue. 2004. Direct observations of the effects of aerosol loading on net ecosystem CO_2 exchanges over different landscapes. *Geophysical Research Letters* 31: L20506, doi: 10.1029/2004GL020915.

- **Intergenerational benefits of CO_2 enrichment.** CO_2 enrichment usually stimulates wheat yield by increasing photosynthesis, but other more indirect mechanisms may also be involved. Two semi-dwarf varieties of spring wheat were grown at both ambient and elevated CO_2 concentrations from seeds produced at elevated CO_2. The process was repeated for 2 additional generations. Many of the traits measured, including aboveground and belowground biomass, responded more to CO_2 enrichment during the second and third generations than first generation. Measured changes of CO_2 response resulted because seeds produced at elevated CO_2 differed in some aspect of composition that proved beneficial to subsequent seedlings grown at elevated CO_2 levels. CO_2 enrichment may stimulate growth and yield of wheat more than predicted from short-term experiments.

Bai, Y., C.R. Tischler, D.T. Booth, and E.M. Taylor. 2003. Variations in germination and grain quality within a rust resistant common wheat germplasm as affected by parental CO_2 conditions. Environmental and Experimental Botany 50:159-168.

Derner, J.D., C.R. Tischler, H.W. Polley, and H.B. Johnson. 2004. Intergenerational above- and belowground responses of spring wheat (*Triticum aestivum L.*) to elevated CO_2. Basic and Applied Ecology 5:145-152.

Topic: Rangelands, Pastures and Wetlands

Goals: Determine how projected global change and management practices/patterns will affect the ecology, hydrology, productivity, and sustainability of North American rangelands; determine how range condition/health can be evaluated in terms of indices of soil C, organic matter, and biodiversity; and develop cost-effective management responses to global change in rangelands.

Projected Impact: Healthy, productive rangeland ecosystems that successfully adapt to global change.

Summary: Effects of elevated CO_2 on grassland systems indicate that impacts of CO_2 on soil water may be of overriding importance in semi-arid grasslands, allowing elevated CO_2 to decrease forage quality, alter species composition, promote invasion by woody species and affect nutrient cycling.

Selected Accomplishments

- **Forage quality declines at elevated atmospheric CO_2 concentrations.** While rising atmospheric CO_2 concentrations may appear beneficial for agriculture by stimulating plant growth, high levels of CO_2 can reduce forage quality, with potentially negative consequences for livestock. The results were obtained from a five-year field experiment in which large, open-top chambers were place over native Colorado shortgrass steppe and CO_2 injected into half of the chambers to evaluate vegetation responses to growth at present-day concentrations of CO_2 and the predicted twice current CO_2 levels. The research showed shifts in plant species composition and reductions in forage N concentrations in response to growth under elevated CO_2, suggesting that as atmospheric CO_2 concentrations continue to rise, forage quality will drop below critical levels required for animal maintenance, and may impair animal performance. The work has received popular press coverage from New York Times, Boston Globe, WHOW Illinois NewsTalk Radio, and U.S. Climate Change Science Program reports concerning the impacts of global climate change on world agriculture.

King, J. Y., A. R. Mosier, J. A. Morgan, D. R. LeCain, D. G. Milchunas, and W. J. Parton. 2004. Plant Nitrogen Dynamics in Shortgrass Steppe Under Elevated Atmospheric CO_2. *Ecosystems* 7:147-160.

Körner, C., J. A. Morgan, and R. Norby. 2007. CO_2 Fertilization: When, Where, and How Much? IN: J. G. Canadell, D. E. Pataki, and L. F. Pitelka (eds.) *Terrestrial Ecosystems in a Changing World*, The IGBP Series, Springer, Berlin. p. 9-22.

Milchunas, D. G., A. R. Mosier, J. A. Morgan, D. R. LeCain, J. Y. King, and J. A. Nelson. 2005. Elevated CO_2 and Defoliation Effects on a Shortgrass Steppe: Forage Quality Versus Quantity for Ruminants. *Agriculture, Ecosystems and Environment* 111:166-184.

Milchunas, D. G., A. R. Mosier, J. A. Morgan, D. R. LeCain, J. Y. King, and J. Y. Nelson. 2005. Root Production and Tissue Quality in a Shortgrass Steppe Exposed to Elevated CO_2: Using a New In-growth Method. *Plant and Soil* 268:111-122.

Morgan, J. A. 2005. Rising Atmospheric CO_2 and Global Climate Change: Management Implications for Grazing Lands. IN: S. G. Reynolds, and J. Frame (eds.) *Grasslands: Developments Opportunities Perspectives*, FAO and Science Pub. Inc. p. 245-272.

Morgan, J. A., A. R. Mosier, D. G. Milchunas, D. R. LeCain, J. A. Nelson, and W. J. Parton. 2004. CO_2 Enhances Productivity, Alters Species Composition, and Reduces Forage Digestibility of Shortgrass Steppe Vegetation. *Ecological Applications* 14:208-219.

Parton, W. J., J. A. Morgan, W. Guiming, and S. J. Del Grosso. 2007. Projected Ecosystem Impact of the Prairie Heating and CO_2 Enrichment Experiment. *New Phytologist* 174:823-834.

- **Rising atmospheric CO_2 alters the botanical structure of the Colorado Shortgrass Steppe.** Rising atmospheric CO_2 has been implicated, without direct evidence, in the encroachment of woody plants into many world grasslands over the past two centuries, a process which is contributing to grassland degradation. Research using large open-top CO_2-fumigation chambers placed over native shortgrass steppe in northern Colorado showed that doubling CO_2 over five years resulted in an 84% increase in productivity of a perennial native grass, *Stipa comata* (needle-and-thread), and a 40-fold increase in aboveground biomass of *Artemisia frigida* (fringed sagewort), a common sub-shrub of some North American and Asian grasslands. Thirty four other plant species showed no response to CO_2. These results illustrate that rising atmospheric CO_2 can affect species changes due to differential species sensitivities to CO_2, and are the first evidence from a manipulative experiment implicating rising atmospheric CO_2 in rangeland woody plant invasions.

Morgan, J. A., A. R. Mosier, D. G. Milchunas, D. R. LeCain, J. A. Nelson, and W. J. Parton. 2004. CO_2 Enhances Productivity, Alters Species Composition, and Reduces Forage Digestibility of Shortgrass Steppe Vegetation. *Ecological Applications* 14:208-219.

Morgan, J. A., D. G. Milchunas, D. R. LeCain, M. S. West, and A. Mosier. 2007. Carbon Dioxide Enrichment Alters Plant Community Structure and Accelerates Shrub Growth in the Shortgrass Steppe. *Proceedings of the Natl. Academy of Sciences, U.S.A.* 104: 14724-14729

- **Soil biology feed-backs under elevated CO_2.** Ecosystem response to global change is largely determined by soil biological activities that control cycling of nutrients and their availability to plants. However, our present understanding of those activities and their role in grassland response to climate change is limited and often contradictory. Using large open-top CO_2-fumigation chambers placed over native shortgrass steppe in northern Colorado, measurements of root growth and dynamics, plant N dynamics, soil trace gas fluxes, and soil microbiology were undertaken to better understand how rising atmospheric CO_2 concentrations will impact soil nutrient cycling, and ultimately, plant responses and carbon storage potential. Growth at elevated CO_2 led to higher net root growth rates, greater plant N assimilation, increased plant deposition of C into soil areas densely occupied by roots, and shifted more of the microbial biomass from bacteria towards fungi. The concentration of N in plant tissues declined because CO_2 stimulated plant growth more than plant N uptake. Further, soil-atmosphere fluxes of N -containing gases responded positively to N additions in CO_2-enriched grassland plots. These last two findings suggest that exposure to elevated CO_2 reduced concentrations of inorganic soil N pools. Collectively, results indicate that ambient CO_2 concentration can have profound changes on soil nutrient cycling. On balance, the greater plant root growth, increased deposition of C into the soil and a shift towards a fungal community all suggest greater potential for C storage as CO_2 rises, although further research is needed to better understand how CO_2 will affect soil CO_2 release through decomposition, which tends to increase under elevated CO_2, and will offset C uptake.

Gill, R. A., R. H. Kelly, W. J. Parton, K. A. Day, R. B. Jackson, J. A. Morgan, J. M. O. Scurlock, L. L. Tieszen, J. van de Castle, D. S. Ojima, and X. S. Zhang. 2002. Using Simple Environmental Variables to Estimate Belowground Productivity in Grasslands. *Global Ecology and Biogeography* 11(1):79-86.

Kandeler, E., A. R. Mosier, J. A. Morgan, D. G. Milchunas, J. Y. King, R. Sabine, and D. Tscherko. 2006. Response of Soil Microbial Biomass and Enzyme Activities to the Transient Elevation of Carbon Dioxide in a Semi-Arid Grassland. *Soil Biology and Biogeochemistry* 38(8):2448-2460.

Kandeler, E., A. R. Mosier, J. A. Morgan, D. G. Milchunas, J. Y. King, R. Sabine, and D. Tscherko. 2009. Transient Elevation of Carbon Dioxide Modified the Microbial Community Composition in a Semi-Arid Grassland. *Soil Biology and Biochemistry*. 40:162-171

King, J., A. R. Mosier, J. A. Morgan, D. R. Lecain, D. G. Milchunas, and W. A. Parton. 2004. Plant Nitrogen Dynamics in Shortgrass Steppe Under Elevated Atmospheric Carbon Dioxide. *Ecosystems* 7:147-160.

LeCain, D. L., J. A. Morgan, D. G. Milchunas, A. R. Mosier, J. A. Nelson, and D. P. Smith. 2006. Root Biomass of Individual Species, and Root Size Characteristics After Five Years of CO_2 Enrichment on Native Shortgrass Steppe. *Plant and Soil* 279:219-228.

Milchunas, D. G., J. A. Morgan, A. R. Mosier, and D. R. LeCain. 2005. Root Dynamics and Demography in Shortgrass Steppe Under Elevated CO_2, and Comments on Minirhizotron Methodology. *Global Change Biology* 11:1837-1855.

Milchunas, D. G., A. R. Mosier, J. A. Morgan, D. R. LeCain, J. Y. King, and J. Y. Nelson. 2005. Root Production and Tissue Quality in a Shortgrass Steppe Exposed to Elevated CO_2: Using a New Ingrowth Method. *Plant and Soil* 268:111-122.

Morgan, J. A. 2002. Looking Beneath the Surface. *Science*. 298:1903-1004.

Mosier, A. R., J. A. Morgan, J. Y. King, D. LeCain, and D. G. Milchunas. 2002. Soil-Atmosphere Exchange of CH_4, CO_2, NO_x, and N_2O in the Colorado Shortgrass Steppe Under Elevated. *Plant and Soil* 240:201-211.

Mosier, A. R., E. Pendall, and J. A. Morgan. 2003. Soil-atmospheric Exchange of Ch_4, CO_2, NO_x, and N_2O in the Colorado Shortgrass Steppe Following Five Years of Elevated CO_2 and N Fertilization. *Atmospheric Chemistry and Physics Discussions* 3:2691-2706.

Parton, W. J., J. A. Morgan, W. Guiming, and S. J. Del Grosso. 2007. Projected Ecosystem Impact of the Prairie Heating and CO_2 Enrichment Experiment. *New Phytologist* 174:823-834.

Pendall E., A. R. Mosier, and J. A. Morgan. 2004. Rhizodeposition Stimulated by Elevated CO_2 in a Semi-Arid Grassland. *New Phytologist* 162:447-458.

- **Rising atmospheric CO_2 affects semi-arid grassland ecology via alterations of soil-plant water relations.** The implications of rising atmospheric CO_2 for plants has focused on plant production through photosynthesis, leaving questions on the response of transpiration. Field research using open-top chambers placed over native Colorado shortgrass steppe demonstrated that consistent and substantive productivity increases of native grasses grown under enriched levels of atmospheric CO_2 were due mostly to the effect of CO_2 on plant-soil water relations, and only secondarily via direct stimulation of photosynthesis. Increasing CO_2 can also slow transpiration, thereby improving plant water use efficiency and reducing the rate of soil moisture depletion. A synthesis report of grassland experiments conducted around the world substantiated the pivotal role of water relations in the responses of native and semi-natural plant communities to rising atmospheric CO_2.

LeCain, D. R., J. A. Morgan, A. R. Mosier, and J. A. Nelson. 2003. Soil and Plant Water Relations, Not Photosynthetic Pathway, Primarily Influence Photosynthetic Responses in a Semi-arid Ecosystem Under Elevated CO_2. *Annals of Botany* 92:41-52.

Nelson, J. A., J. A. Morgan, D. R. LeCain, A. R. Mosier, D. G. Milchunas, and W. J. Parton. 2004. Elevated CO_2 Increases Soil Moisture and Enhances Plant Water Relations in a Long-Term Field Study in the Semi-Arid Shortgrass Steppe of Northern Colorado. *Plant and Soil* 259:169-179.

Morgan, J. A., D. E. Pataki, C. Körner, H. Clark, S. J. DelGrosso, J. M. Grunzewig, A. K. Knapp, A. R. Mosier, P. C. D. Newton, P. A. Niklaus, J. B. Nippert, R. S. Nowak, W. J. Parton, H. W. Polley, and M. R. Shaw. 2004. Water Relations in Grassland and Desert Ecosystems Exposed to Elevated Atmospheric CO_2. *Oecologia* 140:11-25.

- **CO_2 enrichment improves plant water status on grasslands**. As atmospheric CO_2 increases, stomata partially close, resulting in a decrease of conductance to water vapor. Plant and ecosystem-level impacts of reduced stomatal conductance to water remain unclear. Increasing CO_2 from pre-industrial to current higher concentrations on a grassland in central Texas appears to have slowed the rate at which plants depleted soil water, improved plant water status, and increased plant growth per unit of water consumed, but these benefits of CO_2 to plants were no greater over low than higher concentrations. Results indicate that CO_2 enrichment has improved plant water status and lessened plant sensitivity to drought and that water-limited grasslands will continue to benefit from CO_2 enrichment.

Morgan, J.A., D.E. Pataki, C. Körner, H. Clark, S.J. Del Grosso, J.M. Grünzweig, A.K. Knapp, A.R. Mosier, P.C.D. Newton, P.A. Niklaus, J.B. Nippert, R.S. Nowak, W.J. Parton, H.W. Polley, and M.R. Shaw. 2004. Water relations

in grassland and desert ecosystems exposed to elevated atmospheric CO_2. *Oecologia* 140:11-25.

Polley, H.W. 2002. Implications of atmospheric and climatic change for crop yield and water use efficiency. *Crop Science* 42: 131-140.

Polley, H.W., H.B. Johnson, and J.D. Derner. 2002. Soil- and plant-water dynamics in a C_3/C_4 grassland exposed to a subambient to superambient CO_2 gradient. *Global Change Biology* 8: 1118-1129.

- **Shrub and grass land ecosystem water use efficiency and net CO_2 fluxes**. Semiarid grasslands cover a large portion of the Earth's surface, but their role in the C cycle is unclear. Daily measurements of net CO_2 flux were examined for a five-year period (1996-2000) for grasslands in the USDA-ARS Walnut Gulch Experimental Watershed. The linear relationship between instantaneous and daytime net CO_2 flux was combined with daily average wind speed to determine a relation for mapping total daily net CO_2 flux. In addition, plant uptake of CO_2 from the atmosphere and atmospheric concentration reductions are tied to the ecosystem water use efficiency (EWUE) of different plant communities. EWUE is a measure of the amount of carbon dioxide taken up to the amount of water lost through evapotranspiration (ET). Knowing the EWUE of plant communities is important to the understanding the C cycle and how the plant communities interact. The uptake of CO_2 and the loss of water were measured at a shrub and grass site in Arizona. The grass community had 1.4 to 1.6 times higher EWUE with CO_2 uptake into the plant biomass with similar precipitation input. Rangeland managers will use this information to promote grassland establishment and maintenance. Once this additional grassland biomass can be incorporated into long-term SOM storage, there is the potential to reduce the CO_2 concentration in the atmosphere along with reducing the cost to society caused by global warming. The ability to map total daily net CO_2 flux may ultimately be used as a tool for estimating large area CO_2 fluxes and assist in determining the role semiarid grasslands play in the C cycle.

Emmerich, W.E. 2007. Ecosystem Water Use Efficiency in a Semiarid Shrubland and Grassland Community. *Rangeland Ecology and Management*: 60: 464–470

Holifield, C.D., McElroy, S., Moran, M.S., Bryant, R., Miura, T., Emmerich, W.E. 2003. Temporal and spatial changes in grassland transpiration detected using Landsat TM and ETM+ imagery. *Can. J. Rem. Sens*. 29(2):259-270.

- **Stomatal response to CO_2 depends on growth CO_2 concentration.** Stomata regulate the rate at which plants lose water by opening or closing in response to a variety of environmental variables, including atmospheric CO_2 concentration and humidity. To determine whether rising CO_2 concentration changes the number of stomata found on leaves or modifies stomatal sensitivity to CO_2 or humidity, the number of stomates per unit of leaf area and stomatal conductance were measured for grassland species exposed for 4 years to a CO_2 gradient from pre-Industrial to elevated concentrations. Stomatal conductance of a forb declined greatly over pre-Industrial CO_2 concentrations partly because plants grown at low CO_2 levels had fewer, but much larger stomatal pores than did plants grown at current and higher CO_2 levels. Increasing CO_2 did not change stomatal density of four other species, but increased the stomatal density of two species. The >35% increase in atmospheric CO_2 during the last two centuries has altered water requirements of some plants, and thereby influencing water dynamics on grasslands.

Maherali, H., H.B. Johnson, and R.B. Jackson. 2003. Stomatal sensitivity to vapour pressure difference over a subambient to elevated CO_2 gradient in a C_3/C_4 grassland. *Plant, Cell and Environment* 26:1297-1306.

Maherali, H., C.D. Reid, H.W. Polley, H.B. Johnson, and R.B. Jackson. 2002. Stomatal acclimation over a subambient to elevated CO_2 gradient in a C_3/C_4 grassland. *Plant, Cell and Environment* 25: 557-566.

Reid, C.D., H. Maherali, H.B. Johnson, S.D. Smith, S.D. Wullschleger, and R.B. Jackson. 2003. On the relationship between stomatal characters and atmospheric CO_2. *Geophysical Research Letters* 30:1983, doi:10.1029/2003GL017775.

- **Nonlinear responses of grassland processes to CO_2.** Increasing atmospheric CO_2 concentration is likely changing plant and ecosystem properties, including plant growth and water use and rates of soil carbon storage, but changes need not be linear and may exhibit threshold responses that complicate prediction. A grassland in central Texas was exposed to a continuous gradient of CO_2 spanning pre-Industrial to elevated concentrations. Nonlinear and threshold responses to CO_2 were evident in several plant and ecosystem properties, including photosynthesis, stomatal function, and soil C storage and N cycling. Because of the nonlinear nature of CO_2 effects, even relatively small increases in CO_2 concentration may cause dramatic shifts in the structure and function of grasslands, changes for which managers are ill-equipped.

  Gill, R.A., H.W. Polley, H.B. Johnson, L.J. Anderson, H. Maherali, and R.B. Jackson RB. 2002. Nonlinear grassland responses to past and future atmospheric CO_2. *Nature* 417: 279-282.

  Maherali, H., C.D. Reid, H.W. Polley, H.B. Johnson, and R.B. Jackson. 2002. Stomatal acclimation over a subambient to elevated CO_2 gradient in a C_3/C_4 grassland. *Plant, Cell and Environment* 25: 557-566.

- **Shifts in vegetation composition on grassland at elevated CO_2.** The extent of changes of plant productivity and the relative abundance of plant species responding to increases of atmospheric CO_2 concentration is unknown. Above-ground biomass production and plant species composition was measured on a central Texas grassland exposed for four years to a continuous gradient of CO_2 spanning pre-Industrial to current elevated concentrations. Biomass increased dramatically as CO_2 concentration was increased during three of four years, although different species contributed to the positive response of biomass to CO_2 during different years. Increasing CO_2 also accelerated a shift of species composition initiated by release from grazing in which forbs increased in abundance at the expense of warm-season grasses. Results indicate that grasslands may be more productive and contain a different mixture of plant species in the future, changes that are poorly accommodated for in current management schemes for these ecosystems.

  Derner, J.D., H.B. Johnson, B.A. Kimball, P.J. Pinter Jr, H.W. Polley, C.R. Tischler, T.W. Boutton, R.L. LaMorte, G.W. Wall, N.R. Adam, S.W. Leavitt, N.J. Ottman, A.D. Matthias, and T.J. Brooks. 2003. Above- and belowground responses of C_3-C_4 species mixtures to elevated CO_2 and soil water availability. *Global Change Biology* 9: 452-460.

  Polley, H.W., H.B. Johnson, and J.D. Derner. 2003. Increasing CO_2 from subambient to superambient concentrations alters species composition and increases above-ground biomass in a C_3/C_4 grassland. *New Phytologist* 160: 319-327.

- **Plant species diversity.** Plant production on grasslands has been found to respond more to CO_2 enrichment when plant species diversity is high, but controls on diversity and mechanisms by which diversity regulates productivity and its response to CO_2 are unknown. The importance of seed availability and disturbance arising from cattle grazing to the establishment of native plant species and plant species diversity in central Texas grasslands, and effects of both species number and species abundances on grassland productivity were tested. Seedling establishment was increased more by seed addition in grasslands that had not been grazed for 1-3 years than in grasslands that were currently-grazed or from which cattle had been excluded for 6 years, but seed addition had no consistent effect on plant diversity. Plant production was greater in plots with many species, but effects of species number on production were the same whether species were equally abundant or whether some were abundant and others were rare. The increasing disparity in abundance among plant species that is observed on many rangelands may accelerate species loss, but factors other than or in addition to the availability of seeds limit plant establishment and diversity.

  Polley, H.W., B.J. Wilsey, and J.D. Derner. 2003. Do species evenness and plant diversity influence the magnitude of selection and complementarity effects in annual plant species mixtures? *Ecology Letters* 6: 248-256.

Polley, H.W., B. J. Wilsey, and C.R. Tischler. 2007. Species abundances influence the net biodiversity effect in mixtures of two plant species. *Basic and Applied Ecology* 8: 209-218.

Wilsey, B.J., L.M. Martin, and H.W. Polley. 2005. Predicting plant extinction based on species-area curves in prairie fragments with high beta richness. *Conservation Biology* 19: 1835-1841.

Wilsey, B.J. and H.W. Polley. 2002. Reductions in grassland species evenness increase dicot seedling invasion and spittle bug infestation. *Ecology Letters* 5: 676-684.

Wilsey, B.J. and H.W. Polley. 2003. Effects of seed additions and grazing history on species diversity and aboveground productivity of sub-humid grasslands. *Ecology* 84: 920-931.

Wilsey, B.J. and H.W. Polley. 2004. Realistically low species evenness does not alter grassland species-richness-productivity relationships. *Ecology* 85: 2693-2700.

Topic: Pests

Goals: Quantify the growth, seed production, and viability of troublesome weed species and, potential crop losses due to weedy competition at the field level with increasing CO_2 and/or temperature; provide multi-variate analysis of elevated carbon dioxide and other abiotic stresses (UV-B, tropospheric ozone, temperature, drought) on crop susceptibility to pests; assess secondary effects of global change on host plants (e.g., plant water status, N concentration, secondary compounds) and determine if such changes alter susceptibility to pest infestation; determine critical temperature thresholds for troublesome insects and pathogens to identify potential migrants and invaders; provide long-term monitoring of pest populations as an early indicator of climate change effects on agricultural systems; quantify potential changes in pest management strategies with multiple interactions of increasing CO_2 and abiotic stresses; and utilize biological response data to strengthen the ability of simulation models to predict the distribution of pest infestations and projected changes in economic yield for a given abiotic perturbation.

Projected Impact: A sustainable crop production management system that maximizes productivity while minimizing pest damage under changing climate.

Summary: Rising atmospheric CO2 has variety of deleterious impacts related to pests; favoring weed competition over crops, accelerating spread of invasive species and potential or exacerbate human health issues related to allergies and secondary plant alkaloids (e.g. poison ivy).`Weeds, especially invasive species, are often more stimulated by elevated CO_2 than crops or herbaceous species with which they compete, increasing their negative impact, and becoming more difficult to control. Increased need for weed control will directly impact production and economic viability issues facing producers. It was also found with white clover that mite populations and foliar consumption by Western flower thrips increased at elevated CO_2, which has implications for the spread of plant diseases vectored by pests.

Selected Accomplishments

- **Elevated CO_2 favors weeds competition with crops: chemical control of weeds is more difficult, and invasive weeds are more responsive to CO_2.** The effects of rising atmospheric CO_2 on weeds is a significant unknown consideration crop yields. Glyphosate and glufosinate were found to be less effective on weeds grown at elevated CO_2, with currently recommended dosages failing to achieve control. Field experiments showed that elevated CO_2 usually favors C3 weed species in competition with either C3 or C4 crop species. The vegetative growth of invasive weed species has increased much more from pre-industrial to present atmospheric CO_2 levels than is the case for other types of C3 plants, indicating that CO_2 responsiveness may be useful to identify potentially invasive species as the atmospheric CO_2 concentration continues to rise. These results indicate that control of weeds in agriculture may become increasingly difficult and hence, costly, as atmospheric CO_2 rises.

Ziska, L. H. and Goins, E. W. 2006. Elevated atmospheric carbon dioxide and weed populations in glyphosate treated soybean. *Crop Science* 46: 1354-1359.

Ziska, L.H., Faulkner, S.S., and Lydon, J. 2004. Changes in biomass and root:shoot ratio of field-grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO_2: implications for control with glyphosate. *Weed Science* 52:584-588.

Ziska, L. H. 2003. Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *Journal of Experimental Botany* 54: 395-404.

Ziska, L. H. 2003. Evaluation of yield loss in field sorghum from a C_3 and C_4 weed with increasing CO_2. *Weed Science* 51: 914-918.

- **Cheatgrass, fire ecology and rising CO_2.** Spread of the invasive species, cheatgrass (*Bromus tectorum*) over 60 million acres in the Western U.S. has altered fire ecology as this species provides a highly combustible fuel source. Data from three different cheatgrass populations from seed gathered at different elevations in the Sierra Nevada mountain range demonstrated that even small, 50 ppm increases in CO_2 above the 270 ppm pre-industrial average can have significant effects on growth, seed production and combustibility of cheatgrass populations. These data suggest that rising CO_2 has been a potential factor in the ecological success of cheatgrass and may contribute to the number and intensity of cheatgrass-induced fires.

Blank, R.R., White, R., and Ziska, L. H. 2006. Combustion properties of Bromus tectorum L.: Influence of ecotype and growth under four CO_2 concentrations. *International Journal of Wildland Fire* 15:227-236.

Ziska, L.H., Reeves, III J.B., and Blank, R. 2005. The impact of recent increases in atmospheric CO_2 on biomass production and vegetative retention of Cheatgrass (*Bromus tectorum*): implications for fire disturbance. *Global Change Biology* 11:1325-1332.

- **Weeds, climate change and public health**. The human health aspects of weed biology likely to be affected by climate change and rising CO_2 levels are unknown. Direct links between rising CO_2 and climate change, and plant biology and public health were identified including allergic rhinitis caused by increased pollen production of common ragweed, contact dermatitis caused by increased poison ivy growth, urishiol content, and potency, and increased production of secondary plant alkaloids considered poisonous to humans. Initial data have contributed to a greater understanding of weed biology, and have made significant contributions towards defining how climate and rising CO_2 are expected to impact human health, thus helping agriculture institute precautions for maintaining the health of its work force.

Ziska, L. H., George, K., Frenz, D. A. 2007. Establishment and persistence of common ragweed (*Ambrosia artemisiifolia L.*) in disturbed soil as a function of an urban-rural macro-environment. *Global Change Biology* 13:266-274.

Mohan, J. E., Ziska, L. H., Schlesinger, W. H., Thomas, R. B., Sicher, R. C., George, K., and Clark, J.S. 2006. Biomass and toxicity responses of poison ivy (*Toxicodendron radicans*) to elevated atmospheric CO_2. *Proceedings of the National Academy of Sciences*. 103: 9086-9089.

Singer, B. D., Ziska, L. H., Frenz, D. A., Gebhard, D. E., and Straka, J. G. 2005. Increasing Amb a 1 content in common ragweed (*Ambrosia artemisiifolia*) pollen as a function of rising atmospheric CO_2 concentration. *Functional Plant Biology* 32:667-670.

Ziska, L. H., Emche, S. D., Johnson, E. L., George, K., Reed, D. R., and Sicher, R. C. 2005. Alterations in the production and concentration of selected alkaloids as a function of rising atmospheric carbon dioxide and air temperature: implications for ethno pharmacology. *Global Change Biology* 11:1798-1807.

Ziska, L. H., Gebhard, D. E., Frenz, D. A., Faulkner, S., and Singer, B. D. 2003. Cities as harbingers of climate change: Common ragweed, urbanization, and public health. *Journal of Allergy and Clinical Immunology* 111:290-295.

- **CO_2 enrichment promotes woody establishment on grassland.** The >35% increase in atmospheric CO_2 concentration since Industrialization may have indirectly promoted woody invasion of grasslands by reducing the rate at which grasses deplete soil water between rainfall events. To test this possibility, we measured CO_2 effects on the water content of grassland soil and determined the relationship between soil water content and emergence and survival of seedlings of the invasive shrub honey mesquite. Percentage survival of woody seedlings increased from 1.5% to 15% and 28% at the soil water content measured in grassland exposed to pre-Industrial, current, and future CO_2 concentrations. Our results indicate that recent and projected increases in atmospheric CO_2 concentration may hasten the loss of grasslands and the grazing industry that they support by increasing the establishment of seedlings of invasive shrubs like mesquite.

Polley, H.W. H.B. Johnson, and C.R. Tischler. 2002. Woody invasion of grasslands: evidence that CO_2 enrichment indirectly promotes establishment of *Prosopis glandulosa*. *Plant Ecology* 164: 85-94.

Polley, H.W., C.R. Tischler, H.B. Johnson, and J.D. Derner. 2002. Growth rate and survivorship of drought: CO_2 effects on the presumed tradeoff in seedlings of five woody legumes. *Tree Physiology* 22: 383-391.

- **CO_2 enrichment magnifies intra-specific variation in seedling growth of mesquite.** The rise of atmospheric CO_2 concentration could stimulate invasive shrub honey mesquite growth by increasing the biochemical rate at which mesquite plants convert atmospheric CO_2 to plant C, however the uniformity of the effects of CO_2 response among mesquite genotypes is unknown. The effects of doubled atmospheric CO_2 on seedling growth of genotypes collected from across the shrub's geographic distribution in the southwestern U.S were tested. Seedling biomass one month after emergence was 3% to 75% greater at elevated CO_2 concentration depending on genotype. However, CO_2 enrichment did not favor the genotypes that are the largest or fastest-growing at ambient CO_2. Atmospheric CO_2 enrichment could accelerate mesquite encroachment on grasslands by increasing seedling growth, but CO_2 effects on mesquite are not predictable from seedling size or growth rate under current atmospheric concentration.

Derner, J.D., C.R. Tischler, H.W. Polley, and H.B. Johnson. 2005. Seedling growth of two honey mesquite varieties under CO_2 enrichment. *Rangeland Ecology and Management* 58: 292-298.

Polley, H.W., C.R. Tischler, and H.B. Johnson. 2006. Elevated atmospheric CO_2 magnifies intra-specific variation in seedling growth of honey mesquite: an assessment of relative growth rates. *Rangeland Ecology and Management* 59: 128-134.

- **Feeding patterns of arthropod herbivores are altered at elevated CO_2.** Elevated CO_2 in the atmosphere often stimulates plant growth but can also alter plant chemistry leading to changes in infestation and foliar consumption by pests. For example, CO_2-enrichment significantly increased the rate of mite reproduction on white clover. Correlations between mite population and CO_2 concentration increases were significantly positive for foliar nonstructural carbohydrates and significantly negative for foliar N. Leaf consumption by Western flower thrips of clover grown at twice-ambient CO_2 was 90% greater than in plants grown at ambient CO_2. Because Western flower thrips serve as a vector for tomato spotted wilt virus, increased thrip feeding on plants grown under elevated CO_2 might result in increased prevalence of this disease.

Heagle, A.S., J.C. Burns, D.E. Fisher, and J.E. Miller. 2002. Effects of carbon dioxide enrichment on reproduction of twospotted spider mites on white clover. *Environ. Entomol.* 31:594-601.

Heagle, A.S. 2003. Influence of elevated carbon dioxide on interactions between *Frankliniella occidentalis* and *Trifolium repens*. *Enviro. Entomol.* 32: 421-424.

Component IV: Changes in Weather and the Water Cycle at Farm, Ranch, and Regional Scales

Topic: Water and Energy Balance Interaction in Large Heterogeneous Agricultural Systems
Goals: Develop technologies to estimate agricultural, hydrologic, and energy balance parameters from remotely sensed data at multiple scales; develop methods to better detect environmental stress using remote sensing; develop water management strategies more responsive to the effects of global change.

Projected Impact: Informed management and policy decisions by water supply districts, farmers, other resource managers, and policymakers on issues relating to water and energy balances at various scales.

Summary: Remote sensing tools and algorithms developed by ARS scientist are being used by the United States military, State and Federal policy-makers and even have has international impact.

Selected Accomplishments

- Multi-sensor remote sensing algorithms for monitoring at-risk ecosystems. There is a need to enable scaling of ecosystem models from point to watershed and regional scales. Simple algorithms based on multi-temporal and multi-view sensor data were developed to improve the accuracy of regional evapotranspiration estimates. A grassland ecosystem model driven by remote sensing data was developed and applied to a semiarid rangeland in Southeast Arizona. These tools were used to improve grassland management and predict the regional effects of land cover changes due to climate change. The work was funded by a grant from NASA to encourage operational application. The multi-sensor remote sensing algorithm is in use for an operational forest fire risk index in France, as a drought-monitoring index in Africa, and a grassland degradation index in China.

  Qi, J., Marsett, R.C., Heilman, P., Biedenbender, S., Moran, S., Goodrich, D.C. 2002. RANGES improves satellite-based information and land cover assessments in Southwest United States. *EOS, Am. Geophysical Union* 83(51):601, 605-606.

  Holifield, C.D., S. McElroy, M.S. Moran, R. Bryant and T. Miura 2003. Temporal and spatial changes in grassland transpiration detected using Landsat TM and ETM+ imagery, *Canadian J. of Rem. Sens*. 29:259 270.

  Nouvellon, Y., Moran, M.S., Lo Seen, D., Bryant, R.B., Ni, W., Begue, A., Chehbouni, A.G., Emmerich, W.E., Heilman, P.,Qi, J. 2001. Coupling a grassland ecosystem model with Landsat imagery for a 10-year simulation of carbon and water budgets. *Remote Sensing of Environment*. 78. 131-149.

- **Improved soil moisture estimates from Synthetic Aperture Radar (SAR)**. Maps of soil moisture are critically needed for environmental modeling and management decisions. A simple image differencing technique was found to better estimate soil moisture from SAR than a more complex model because rock fragments negatively affect the sensitivity of the more complicated model. Improved methods for remote soil moisture estimation may enable near-surface soil moisture mapping for use by hydrologic and plant growth models, ranchers, farmers, and by planners of military cross country vehicle mobility. The new method was demonstrated at the U.S Army Topographic Engineering Center during 2005 and 2007 operational implementation is underway.

  Moran, M.S., C.D. Peters-Lidard, J.M. Watts, and S. McElroy. 2004. Estimating soil moisture at the watershed scale with satellite-based radar and land surface models, *Canadian J. Rem. Sens*. 30:1-22.

Thoma, D., Moran, M.S., Bryant, R., Rahman, M.M., Holifield Collins, C.D., Skirvin, S.M., Sano, E.E., Slocum, K. 2005. Comparison of four models for determining surface soil moisture from c-band radar imagery. *Water Resour. Res*. 42(1): 1-12.

Bryant, R., Moran, M.S., Thoma, D., Holifield Collins, C.D., Skirvin, S.M., Rahman, M., Slocum, K., Starks, P.J., Bosch, D.D., Gonzalez-Dugo, M.P. 2007. Measuring surface roughness to parameterize radar backscatter models for retrieval of surface soil moisture. *IEEE Geosci. and Rem. Sens. Letters* 4(1): 137-141.

Tischler, M., Garcia, M., Petrs-Lidard, C., Moran, M.S., Miller, S., Thoma, D., Kumar, S., Geiger, J. 2007. A GIS framework for surface-layer soil moisture estimation combining satellite radar measurements and land surface modeling with soil physical property estimation. *Environmental Modeling & Software* 22:891-898.

- **Automated continental scale mapping of evapotranspiration (ET) and moisture stress.** Accurate course-scale maps of ET are needed to determine regional patterns of soil water consumed daily by native and managed vegetation, and the effects of moisture deficiencies on water use and plant growth. An automated modeling technique using thermal remote sensing data from geostationary satellites to estimate ET and other land-surface fluxes was developed. Model ET estimates agree well with tower and aircraft flux data, and spatial ET pattern anomalies coincide with precipitation anomalies, indicating an ability to detect moisture stress conditions. The method is a significant improvement over previous, largely empirical methods, as it uses a combination of climate, soil, and vegetation factors influencing surface energy balance. The automated aspect of the method allows web-based posting of the maps for multiple users ranging from individual producers and land managers to strategic decision makers.

Anderson, M.C., Norman, J.M., Kustas, W.P., Li, F., Prueger, J.H., Mecikalski, J.R. Effects of vegetation clumping on two-source model estimates of surface energy fluxes from an agricultural landscape during SMACEX. 2005, *Journal of Hydrometeorology*. 6: 892-909.

Krajewski, W.F., Anderson, M.C., Eichinger, W.E., Entekhabi, D., Hornbuckle, B.K., Houser, P.R., Katul, G.G., Kustas, W.P., Norman, J.M., Peters-Lidard, C., Wood, E.F. 2006. A Remote Sensing Observatory for Hydrologic Sciences: A Genesis for Scaling to Continental Hydrology, 42, doi:10.1029/2005WR004435. *Water Resources Research.*

Kustas, W.P., Anderson, M.C., French, A.N., Vickers, D. 2006. Using a Remote Sensing Field Experiment to Investigate Flux-Footprint Relations and Flux Sampling Distributions for Tower and Aircraft-based Observations. *Advances in Water Resources.* 29:355-368.

Anderson, M. C., W. P. Kustas, and J. M. Norman. 2007. Upscaling flux observations from local to continental scales using thermal remote sensing, *Agron. J.*, 99, 240-254.

Anderson, M. C., J. M. Norman, J. R. Mecikalski, J. A. Otkin, and W. P. Kustas. 2007. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation, *J. Geophys. Res.,* 112, D10117, doi:10.1029/2006JD007506.

Anderson, M. C., J. M. Norman, J. R. Mecikalski, J. A. Otkin, and W. P. Kustas. 2007. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 2. Surface moisture climatology, *J. Geophys. Res*., 112, D11112, doi:10.1029/2006JD007507.

- **Large area hydrologic requirements of and ET by riparian vegetation along the San Pedro River, AZ**. The significant quantities of groundwater and surface water transpired by arid and semiarid riparian ecosystems are a major component of the overall water budget and need to be quantified. Annual ET was quantified for five different and predominant riparian land cover types at six different sites along the San Pedro River of southeastern Arizona. This information was used in conjunction with meteorological, hydrological, and geographical data to estimate total reach-scale groundwater use for different riparian segments within the Upper San Pedro Basin. This experiment and the methods developed proved to be a major first step in the emergent field of Eco-hydrology. This experimental design and methodology has been adopted by investigators from New Mexico State, the Univ. of New Mexico and Los Alamos National Laboratory to estimate riparian ET in the Rio Grande and by investigators from the Univ. of Arizona to estimate riparian ET in the Kern River in California. The riparian ET estimates were also a key component of the biological opinion issued by the U.S. Fish and Wildlife Service to the Ft. Huachuca Army base in relation to sufficient water for endangered species in the San Pedro riparian system. They are also a critical groundwater boundary condition for the basin groundwater model developed by the Upper San Pedro Partnership to carry out its congressionally mandated task of managing the Upper San Pedro Basin (Sec. 321 of Public Law 108-136). These results were also essential to developing new remote sensing techniques and methods to estimate riparian vegetation water use along many important western U.S. watercourses.

Huxman, T.E., Wilcox, B.P., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K.R., Pockman, W.T., Jackson, R.B. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* 86:308-319.

Nagler, P.L., Scott, R.L., Westenburg, C., Cleverly, J.R., Glenn, E.P., Huete, A.R. 2005. Evapotranspiration on western U.S. rivers estimated using the enhanced vegetation index from MODIS and data from eddy covariance and Bowen ratio flux towers. *Rem. Sens. Environ*. 97(3): 337-351.

Gazal, R.M., Scott, R.L., Goodrich, D.C., Williams, D.G. 2006. Controls on transpiration in a desert riparian cottonwood forest. *Ag. & Forest Meteorology*. 137(56-67).

Farid, A., Goodrich, D.C., Bryant, R., Sorooshian, S. 2007. Using Airborne Lidar to Predict Leaf Area Index in Cottonwood Trees and Refine Riparian Water Use Estimates. *J. of Arid Environments*, 2007. (In press).

- **NEXRAD Radar rainfall products improved with ARS Experimental Watersheds Data.** Accurate rainfall estimates from NEXRAD radar would enable numerous applications. Analysis of NEXRAD rainfall estimates revealed estimates lower than those from five ARS experimental watershed rain gauge networks. Discovery of temporal and spatial scale-dependencies in the NEXRAD radar-reflectivity-rainfall intensity relationship over the ARS Walnut Gulch Experimental Watershed led to development of a new radar data-based rainfall model that compensates for these dependencies. Use of revised NEXRAD rainfall estimates in a rainfall-runoff model produced improved runoff estimates. NEXRAD total annual rainfall estimates may be unsuitable for model-based evaluations of the long-term effectiveness and economic viability of agricultural management practices. The utility of radar rainfall estimates for extreme-event flooding, runoff, and erosion requires more detailed analysis of radar and gauge data for individual storms within a given watershed location in the semi-arid southwest. The work resulted in a Collaborative research undertaken with scientists from the National Weather Service in a NWS funded joint COMET research project.

Morin, E., Krajewski, W., Goodrich, D.C., Gao, X., Sorooshian, S. 2003. Estimating rainfall intensities from weather radar data: the scale dependency problem. *Journal of Hydrometeorology*. 4:782-797.

Morin, E., Maddox, R.A., Goodrich, D.C., Sorooshian, S. 2005. Radar Z-R relationship for summer monsoon storms in Arizona. *J. Weather and Forecasting*, 20(4):672–679.

Morin, E., Goodrich, D.C., Maddox, R.A., Gao, A., Gupta, H.V., Sorooshian, S. 2005. Rainfall modeling for integrating radar information into hydrological model, *Atmospheric Science Letters*, Published Online: 22 Feb 2005, DOI: 10.1002/asl.86

Morin, E., Goodrich, D.C., Maddox, R.A., Gao, X., Gupta, H.V., Sorooshian, S. 2006. Spatial patterns in thunderstorm rainfall events and their coupling with watershed hydrological response. *Adv. in Water Resources*. 29:843-860.

Topic: Land Use and Land Cover

Goals: Develop improved methods to map plant species from remote sensing; develop models and prediction methodologies to assess vegetation succession under varying CO_2, climate, and management scenarios; develop improved models to assess regional water supply, water quality, agricultural production and economic consequences of land cover change.

Projected Impact: Sustainable agricultural systems for farm, range, and forest lands.

Summary: ARS has specifically contributed to improved understanding of these processes and developed tools to help estimate the impacts of land cover change, including ecohydrological impacts of woody plant encroachment and the hydrologic and water quality impacts of land cover change. For example the Automated Geospatial Watershed Assessment (AGWA) tool for hydrologic and water quality impacts of land cover change has been downloaded by over 1200 users from local, state and federal agencies; universities; environmental groups; and, consulting firms, and internationally in over 75 countries.

Selected Accomplishments

- **Ecohydrological impacts of woody plant encroachment.** Quantification of the impact of invasive woody species on hydrology is needed to develop land management practices more responsive to global change. Seasonal patterns of water and CO_2 exchange were quantified for three ecosystems located on an encroachment gradient in southeastern Arizona. This study was one of the first to assess whole ecosystem fluxes to determine the impacts woody plant encroachment.

  Huxman, T.E., Wilcox, B.P., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K.R., Pockman, W.T., Jackson, R.B. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* 86:308-319.

  Scott, R.L., Huxman, T.E., Williams, D.G., Goodrich, D.C. 2006. Ecohydrological impacts of woody plant encroachment: Seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. *Global Change Biology*, 12:311–324.

  Potts, D.L., Huxman, T.E., Scott, R.L., Williams, D.G., Goodrich, D.C. 2006. The sensitivity of ecosystem carbon exchange to seasonal precipitation and woody plant encroachment. *Oecological* 150(3):453-463.

- **Climate change effects on erosion**. An understanding of climate change impacts on soil erosion rates is needed to ensure that agriculture can adapt to climate change. Studies of how current trends of rainfall distributions and intensities, and projected changes of temperature, solar radiation, and atmospheric CO_2 concentrations were conducted to address could affect soil erosion rates. Results indicate that if U.S. and European precipitation trends of the last century continue without land cover changes, erosion could increase by 25 to 55% over the next century. Results also show how farm response to climate change can potentially exacerbate, or ameliorate the changes of expected erosion rates. Management strategies, conservation practices and programs will have to shift in response to climate change for sustained production.

  Nearing, M.A., Pruski, F.F., Oneal, M.R. 2004. Expected climate change impacts on soil erosion rates: a review. *Journal of Soil and Water Conservation* 59(1):43-50.

  Pruski, F.F., Nearing, M.A. 2002. Climate-induced changes in erosion during the 21st century for eight U.S. locations. *Water Resources Research*. 39(12):34-1-34-11.

  Zhang, X.J., Nearing, M.A., Garbrecht, J.D., Steiner, J.L. 2004. Downscaling monthly forecasts to simulate impacts of climate change on soil erosion and wheat production. *Soil Science Society of America Journal*. 68:1376-1385.

- **Automated Geospatial Watershed Assessment (AGWA) tool for hydrologic and water quality impacts of land cover change**. The PC-based AGWA provides rapid qualitative estimates of runoff and erosion relative to land use change via rapid use and application of the ARS SWAT and KINEROS watershed models. AGWA was developed by ARS and EPA. It has been used for post-fire watershed assessments, assessments of the hydrologic impacts of 25 years of land-cover change, alternative futures assessments, graduate and undergraduate education, and education of municipal officials for watershed planning. AGWA, its documentation, fact sheet, and tutorials can be downloaded at (http://www.tucson.ars.ag.gov/agwa). AGWA has been downloaded by over 1200 users from local, state and federal agencies; universities; environmental groups; and, consulting firms, and internationally in over 75 countries.

Miller, S. N., Kepner, W. G., Hernandez, M., Miller, R. C., Miller, Goodrich, D. C., Heggem, D. L., Mehaffey, M. L., Devonald, F. Kim, and Miller, P. 2002. Integrating landscape assessment and hydrologic modeling in land cover change analysis. *J. American Water Resources Association*, 38(4):915-929.

Miller, R.C., Guertin, D.P., Heilman, P. 2004. Information technology in watershed management decision making. *J. American Water Resources Association*. 40(2):347-357.

Kepner, W.G., Semmens, D.J., Bassett, S.D., Mouat, D.A., Goodrich, D.C. 2004. Scenario analysis for the San Pedro river, analyzing hydrological consequences of a future environment. *J. Environmental Monitoring and Assessment* 94: 115-127.

Miller, S.N., Semmens, D.J., Goodrich, D.C., Hernandez, M., Miller, R.C., Kepner, W.G., Guertin, D.P. 2006. The Automated Geospatial Watershed Assessment Tool. *J. Environmental Modeling and Software*. 22:365.377

Technology Transfer: Miller, S.N., Semmens, D., Miller, R.C., Hernandez, M., Goodrich, D.C., Miller, W.P. 2002. Automated geospatial watershed assessment (AGWA) - A GIS-based hydrologic modeling tool: Documentation and User Manual. USDA Misc. Pub., Software and User Manual Public Release, download at http://ww. tucson.ars.ag.gov/agwa. (Modeling System - web site; documentation and distribution)

Technology Transfer: EPA AGWA Web Site which mirrors the ARS Web Site at: http://www.epa.gov/nerlesd1/land-sci/agwa/index.htm

Technology Transfer: KINEROS Web Site: Documentation and User Manual. USDA Misc. Pub., Software and User Manual Public Release, download at: http://www.tucson.ars.ag.gov/kineros/

Technology Transfer: AGWA Version 1.5 Produce Release. EPA/600/R-02/046 (pdf) at: http://www.epa.gov/nerlesd1/land-sci/agwa/info.htm#product

Technology Transfer: AGWA – A GIS-Based Hydrology Modeling Tool (Fact Sheet): EPA/600/R-02/046 (pdf) at: http://www.epa.gov/nerlesd1/land-sci/agwa/info.htm#product

- **Experimental watershed long-term database**. A data archive that contains hundreds of spectral images and entries for associated ground data from 1990 to the present for the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) was developed. A multi-year modernization of all WGEW instrumentation with near real-time telemetry was completed. A Geo-Data Browser was developed in cooperation with EPA for WGEW and San Pedro River. The combination of the WGEW image archive and an operational method for atmospheric correction have encouraged long-term investigations of natural resources to answer critical questions regarding resource management and effects of climate changes. These images are the basis for numerous national and international studies of land surface change, and have resulted in funded projects by NASA and NSF at ARS watersheds. Based largely on this work, and the long-term, high-quality hydrologic data collection conducted over decades by ARS, the WGEW was chosen as one of only 15 core sites worldwide by the International Community Earth Observing System (CEOS) for satellite product validation and calibration (see http://landval.gsfc.nasa.gov/MODIS/coresite.php?SiteID=22). WGEW re-instrumentation has enhanced both the accuracy and timeliness of the flow of critical research data to ARS, other Federal researchers, ranchers, consultants as well as to the public for activities ranging from cattle grazing allocations, to design of flood control and transportation bridge structures. The San Pedro Data Browser is the most highly hit site of the EPA Landscape Ecology Branch and numerous researchers and consultants are using this data.

Moran, M.S., R. Bryant, C.D. Holifield and S. McElroy. 2003. Refined empirical line approach for retrieving surface reflectance from EO-1 ALI images, *IEEE Rem. Sens. and Geoscience* 41:1411 - 1414.

Bryant, R., M.S. Moran, S. McElroy, C.D. Holifield, K. Thome, T. Miura and S.F. Biggar. 2003. Data continuity of Earth Observing One (EO-1) Advanced Land Imager (ALI) and Landsat TM and ETM+, *IEEE Rem. Sens. and Geoscience* 41:1204-1214.

Moran, S., G. Fitzgerald, A. Rango, C. Walthall, E. Barnes, W. Bausch, T. Clarke, C. Daughtry, J. Everitt, D. Escobar, et al. 2003. Sensor development and radiometric correction for agricultural applications, *Photog. Eng. Rem. Sens*. 69:705-718.

Technology Transfer: Kepner, W.G., Semmens, D.J, Heggem, D.T., Evanson, E.J., Edmonds, C.M., Scott, S.N., Ebert, D.W., The San Pedro River Geo-Data Browser and Assessment Tools, http://www.epa.gov/nerlesd1/land-sci/san-pedro.htm

Topic: Changes in Water Availability

Goals: Develop methods to assess the impact of global change on the timing and availability of water for agricultural, industrial, and domestic uses; develop methods to assess the changing water requirements of agricultural crops under increasing atmospheric CO_2; develop improved weather generation models that quantify the effects of ENSO and other large-scale weather processes as affected by global change; develop models that provide probabilistic forecasts of precipitation, runoff, and available soil water under anticipated climatic changes.

Projected Impact: Improved management of the water supply for sustaining agricultural production while protecting the environment, including improved models, data bases, and other tools available to water resource managers for assessing the effects of global change on the availability of water for agricultural and domestic uses.

Summary: For many regions of the world, satellite estimates of precipitation cannot be validated due to the lack of well-distributed, ground-based precipitation observations. To enhance our capability to detect potential large area water cycle trends over data poor, but agriculturally important regions, expensive gauging networks must be developed and maintained or independent remote methods of validation must be developed. ARS scientists developed new validation techniques for satellite precipitation retrievals with remotely derived soil moisture estimates as stated by the specific accomplishments listed below.

Selected Accomplishments

- **New validation techniques for satellite precipitation retrievals.** Global scale precipitation measurements derived from satellite sources cannot be validated easily for data-poor locations. A technique to cross-validate remotely-sensed precipitation estimates using satellite-based soil moisture retrievals was developed. The approach can enhance our ability to observe the magnitude and trend of precipitation accumulations over agricultural production regions of the globe. This research will lead to better understanding of the potential impacts of global climate change on agricultural production.

Crow, W.T. and J.D. Bolten. 2007. Estimating precipitation errors using spaceborne surface soil moisture retrievals. *Geophysical Research Letters.* 34:L08403. doi:10.1029/2007GL029450.

Topic: Climate and Weather Variability and Extremes

Goals: Develop quantitative descriptions of climate and weather variability at day-to-decade and farm-to-regional scales; predict agricultural productivity, conservation impacts and watershed response to the variability, and develop production, management, and mitigation alternatives for the conditions; assess use of climate forecasts by producers and agribusiness and develop interface tools to enhance the value of forecasts; incorporate NOAA's seasonal climate forecasts into risk- management, and conservation tools; identify related agro-climatic risk parameters for use with forecasts; improve weather generation models to reflect fine-scale fluctuations and extremes associated with global-scale atmospheric phenomena.

Projected Impact: More sustainable and profitable agricultural systems informed by climate and weather variation and forecasts.

Summary: ARS research has specifically contributed to improved understanding of the impacts of weather and climatic variability at the farm and ranch scale. Accomplishments addressed precipitation event sizes and intervals that control grassland productivity; quantification of the utility of seasonal climate forecasts for agricultural applications; quantified the reduced dependability of seasonal climate forecast downscaling for farm level applications and how multi-year precipitation variations impact water resources management and conservation.

Selected Accomplishments

- **Grassland productivity response to precipitation event sizes and intervals.** The effects of predicted rainfall variability on C cycling processes were investigated with sixteen treatments of differing irrigation intervals and water quantities applied to mesocosms containing mixtures of Great Plains tallgrass prairie species. The response of C cycling processes to rainfall quantity depended on event size and interval. Interactions between rainfall event size and interval may be as important as the total annual quantity of rainfall for C cycling on grasslands.

  Porporato, A., G. Vico, and P.A. Fay. 2006. Superstatistics of hydro-climatic fluctuations and interannual ecosystem productivity. *Geophysical Research Letters* 33: 15402-15405.

- **Utility of NOAA seasonal climate forecasts quantified**. Maps of utility measures for NOAA's seasonal precipitation and air temperature forecasts based on forecasts issued between 1997 and 2005 across the contiguous U.S. were developed. Utility values varied by geographic region and were different for precipitation and air temperature forecasts. The utility maps identified regions where utility measures are higher and where seasonal forecasts currently appear to offer opportunities for incorporation of climate forecast-derived information in agricultural decision support systems. Impacts of climate forecast-derived agronomic guidance include reduced production risk, enhanced profitability, and increased sustainability of agricultural systems.

  Schneider, J. M., and J. D. Garbrecht. 2006. Dependability and Effectiveness of Seasonal Forecasts for Agricultural Applications. *Transactions of the American Society of Agricultural and Biological Engineering* (ASABE), 49(6):1737-1753.

  Garbrecht, J. D., H. Meinke, M. V. K. Sivakumar, R. P. Motha, and M. J. Salinger. 2005. Seasonal Climate Forecasts and Adoption by Agriculture. Earth Observing System, EOS, *Transactions of the American Geophysical Union*, 86(24):227.

  Steiner, J. L., J. M. Schneider, J. D. Garbrecht, and X. J. Zhang. 2004. Climate Forecasts: Emerging Potential to Reduce Dryland Farmers' Risks. Crop Science Society of America and American Society of Agronomy, 677 S. Segoe Rd., Madison, WI53711, USA. C*hallenges and Strategies for Dryland Agriculture.* CSSA Special Publication No. 32, p. 47-65. (Book Chapter)

  Schneider, J.M., and J. D. Garbrecht. 2003. A measure of the usefulness of seasonal precipitation forecasts for agricultural applications. *Transactions of the American Society of Agricultural Engineers,* 46(2):257-267.

- **Multi-year precipitation variations impact water resources management and conservation**. The existence and impact of multi-year precipitation variations on soil erosion, sediment transport and watershed sediment yield were identified and publicized. The magnitude and amplification of the impacts of these variations on watershed runoff and sediment yield in the Southern Great Plains were demonstrated. Consideration of multi-year precipitation variations and associated impacts on watershed runoff and sediment yield reduces risk in water resource management and improves assessment of conservation needs to mitigate water quality and sedimentation problems in downstream water bodies. The visualization of multi-year precipitation variations has been adopted as a product by the Oklahoma Climatological Survey and used by local newspapers to illustrate the alternating and recurring drought and pluvial periods in the historical precipitation record.

Garbrecht, J. D., J. L. Steiner, and C. A. Cox. 2007. Climate Change Impacts on Soil and Water Conservation. Earth Observing System, EOS, *Transactions of the American Geophysical Union*, 88(11):136.

Garbrecht, J. D., P. J. Starks, and J. L. Steiner. 2006. The Under-Appreciated Climate Factor in CEAP. *Journal of Soil and Water Conservation*, 61(4):110-112.

Zhang, X.C. 2006. Spatial Sensitivity of Predicted Soil Erosion and Runoff to Climate Change at Regional Scales. *J. of Soil and Water Conservation* 61(2) 58-64.

Garbrecht, J. D., and T. C. Piechota. 2005. Water Resources and Climate. In *Climate Variations, Climate Change, and Water Resources Engineering,* Garbrecht J. D. and T. C. Piechota (Eds). American Society of Civil Engineers, Reston Virginia. pp. 19-33.

Garbrecht, J. D., Schneider, J. M., and G. O. Brown. 2005. Decade-Long Precipitation Variations and Water Resources Management. In *Climate Variations, Climate Change, and Water Resources Engineering*, Garbrecht J. D. and T. C. Piechota (Eds). American Society of Civil Engineers, Reston Virginia. pp. 37-50.

Piechota, T. C., Garbrecht, J. D., and J. M. Schneider, 2005. Climate Variability and Climate Change. In *Climate Variations, Climate Change, and Water Resources Engineering*, Garbrecht J. D. and T. C. Piechota (Eds). American Society of Civil Engineers, Reston Virginia. p. 3-18.

Garbrecht, J., M Van Liew, and G. O. Brown. 2004. Trends in Precipitation, Streamflow and ET in the Great Plains. *Journal of Hydrologic Engineering,* 9(5):360-367.

Van Liew, M. W., J. D. Garbrecht, and J. G. Arnold. 2003. Simulation of the Impacts of Flood Retarding Structures on Streamflow for a Watershed in Southwestern Oklahoma Under Dry, Average, and Wet Climatic Conditions. *Journal of Soil and Water Conservation*, 58(6):340-348.

Zhang, X.C. Assessing Seasonal Climatic Impact on Water Resources and Crop Production using CLIGEN and WEPP Models. *Transactions of the American Society of Agricultural Engineers.* 2003. v. 46(3). p. 685-693.

Garbrecht, J., and F. Rossel. 2002. Decade-Scale Precipitation Increase in the Great Plains at the End of the 20th Century. *Journal of Hydrologic Engineering*, 7(1):64-75.

- **Deep aquifer recharge from ephemeral streams can be a major portion of the overall inputs to the basin water balance during wet monsoon years**. This was verified by comparing six simple to complex techniques (e.g. water balance-two forms, geochemical-two forms, temperature transport, and microgravity) within a well-controlled field experiment. Ephemeral stream channel recharge can be further augmented by building recharge basins in the floodplain. Research demonstrated that deep basins are needed to store the initial flow and to settle suspended materials, after which the water can flow into shallow basins that can be effectively managed for groundwater recharge. In addition, if water of poor quality is to be stored in basins for future use, research demonstrated that the threat of that water contaminating other surface or groundwater can be greatly reduced by sealing these ponds (i.e., seepage reduced by an order of magnitude) by adding a soil slurry to the pond rather than applying the same material dry to the pond bottom. Projected long-term shortages of water in the Western United States, which are likely to be magnified by global climate change and an expanding population have resulted in the need to increase reliable water supplies. Flood flows that cannot be captured by dams are a potential new source of groundwater recharge. The Upper San Pedro Partnership is utilizing these estimates in developing a new groundwater model of the basin and will use a subset of these methods to fulfill congressionally mandated reporting of annual basin recharge and to develop a plan to bring the basin in balance by 2011 (Sec. 321 of Public Law 108-136). Methods to manage storm flows to reduce clogging or enhance sealing are becoming common practice in many arid and semiarid areas of the west (e.g. City of Phoenix, Metropolitan Water District of Southern California, and internationally).

Bouwer, H. 2002. Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal* 10(1):121-142.

Bouwer, H., J. Ludke, and R.C. Rice. 2001. Sealing pond bottoms with muddy water. *Ecological Engineering* 18(2):233-238.

Goodrich , D.C. , D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Coes, and S. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona, in *Groundwater Recharge in a Desert Environment: The Southwestern United States*, edited by J.F. Hogan, F.M. Phillips, and B.R. Scanlon, Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C., 77-99

Topic: Changing Snowpack Accumulation and Seasonal Water Yield

Goals: Develop methods for aereal snowpack assessment that integrate remote sensing data with traditional techniques; develop noncalibrated, distributed snowmelt runoff models that use remote sensing data and can be used with future climate change inputs; provide tools to water managers and farmers that enable climate change strategies for the future.

Projected Impact: Informed planning for water supply availability throughout the 21st century for irrigated agriculture, hydropower, other domestic supplies, and recreation.

Summary: A physically based model of snowmelt will enable water and irrigation managers to assess the impacts of climate change scenarios to improve operating rules and water use efficiency. ARS research has developed improved models to address the issue of forecasting snowmelt for watersheds in North America.

Selected Accomplishments

- **Snowmelt Forecast Model for North American watersheds**. Snow accumulation, redistribution and melt are dependent upon variable terrain and vegetation, making snowmelt modeling complex and difficult. The ISNOBAL model was developed and tested for wind re-distribution effects of topography and vegetation and spatially-distributed energy balance of snowmelt across a range of watershed environments from California to northern Canada. This research lays the groundwork for wider application of site-specific spatially relevant models to hydrologic analysis and snowmelt forecasting issues. Advances in modeling snow accumulation, redistribution and melt allow resource management agencies to improve estimates of snow cover and streamflow in semi-arid basins.

  Winstral, A., Marks, D. 2002. Simulating wind fields and snow redistribution using terrain-based parameters to model snow accumulation and melt over a semi-arid mountain catchments. *Hydrological Processes*, 16:3585-3603.

- **Improving snowmelt runoff forecasts and evaluation of climate change effects on snowmelt water supply.** The Snowmelt Runoff Model (SRM) has been modified to provide short-term streamflow forecasts for tributaries of the Rio Grande basin and long-term assessments of climate change effects on changes in water supply from snowmelt basins. Forecasting of flow using satellite data and SRM is quite accurate for several weeks to several months with or without updating on the Rio Grande near Del Norte, CO. A 5°C increase in temperature over the next century on the same Del Norte basin, results in a five-week earlier snowmelt runoff peak in the spring with a major change in monthly streamflow volumes. March runoff volume increases by 451% at a time when reservoirs may be at or near capacity whereas July runoff volume decreases by 50% at a time when water availability is already diminished due to agricultural irrigation compared to present day conditions. These assessment techniques are included in the current version of the model.

Rango, A. 2006. Snow: The real water supply for the Rio Grande basin. *New Mexico Journal of Science,* 44: 99-118.

Topic: Scaling of Climate Change to Field, Farm, Ranch and Regional Scales

Goal: Simulate dominant hydrological processes for given space-time weather patterns; predict soil water movement and plant response over a range of space-time scales applicable to sustainable agricultural management practices; integrate impacts of topographically-induced spatial heterogeneity on plant water use and production at management scales so that the results of estimated global change can be downscaled to the management scale and feedback from the ground can be upscaled to the GCM; and incorporate soil freezing and runoff algorithms into our snow models.

Projected Impact: Better rangeland management and more accurate description of forecast global change effects on water supply

Summary: Downscaled temperature forecasts retain 76% of their dependability, while precipitation forecasts retain 66% of their dependability. Dependable forecasts for above average air temperature emerge as worthy of consideration for use in agricultural applications over the majority of the contiguous US. Forecasts for cooler than average air temperature do not retain sufficient net dependability after downscaling to be useful for any part of the contiguous US.

Selected Accomplishments

- **Seasonal climate forecast dependability is reduced by downscaling for farm level applications**. Seasonal climate forecasts cover too large an area and too long a time period (3 months) to provide dependable agricultural decision support information. Forecasts need to be downscaled to sub-county scale and one-month forecasts to hold potential for local agricultural production management and conservation efforts. The loss of dependability from downscaling, and whether enough dependability would remain to justify use of the climate forecasts, is unknown. Research determined that downscaled temperature forecasts retain 76% of their dependability, while precipitation forecasts retain 66% of their dependability. Dependable forecasts for above average air temperature emerge as worthy of consideration for use in agricultural applications over the majority of the contiguous US. Forecasts for cooler than average air temperature do not retain sufficient net dependability after downscaling to be useful for any part of the contiguous US. Forecast divisions where agricultural decision support might benefit from dependable NOAA/CPC seasonal precipitation forecasts are located in Florida, south Texas, southwest New Mexico, Arizona, central and southern California, and parts of Oregon, Washington, Idaho, and Montana. For regions of the US. where climate forecasts exhibit sufficient dependability, downscaling offers opportunities to guide agronomic recommendations that minimize climate-related risks and optimize agricultural resource management. These findings enhance our ability to translate seasonal climate forecasts into statements of risk for local applications and lead to a broader use of seasonal climate forecasts.

Zhang, X.C. 2007. A comparison of explicit and implicit spatial downscaling of GCM output for soil erosion and crop production assessments. *Climatic Change*, (*In press*).

Garbrecht, J. D., J. M. Schneider, and M. W. Van Liew. 2006. Monthly Runoff Predictions Based on Rainfall Forecasts in a Small Oklahoma Watershed. *Journal of the American Water Resources Association*, 42(5):1285-1295.

Zhang, X.C. 2005. Spatial Downscaling of Global Climate Model Output for Site-Specific Assessment of Crop

Production and Soil Erosion. *Agricultural and Forest Meteorology*, 135:215-229.

Schneider, J. M., J. D. Garbrecht, and D. A. Unger. 2005. A Heuristic Method for Time Disaggregation of Seasonal Climate Forecasts. *Weather and Forecasting*, 20:212-221.

Zhang, X. C., M. A. Nearing, J. D. Garbrecht, and J. L. Steiner. 2004. Downscaling Monthly Forecasts to Simulate Impacts of Climate Change on Soil Erosion and Wheat Production. *Soil Science Society of America Journal*, 68:1376-1385.

Summary

The NP 204 research accomplishments highlight ARS scientific and technical contributions to understanding the causes and consequences of some major environmental factors and processes associated with climate change. The knowledge gained from ARS sponsored research projects, and the technologies that have been devised, will enable effective management of agricultural ecosystems for sustained production of food, fiber, fuel and other ecosystem services under a changing environment. The research provides insights to the chemical, physical and biological factors that are either affected, or are affecting environmental changes expected to impact the Nation's natural resources and agricultural ecosystems. The goal of ARS climate change research has been to provide the scientific basis for technologies that enable agricultural ecosystems to adapt to the changes and variations of climate, or alternatively, to develop strategies that mitigate the impact of climate change on agricultural systems. Given the dependence of agricultural systems on soil, water and air for optimum and economical production of agricultural commodities, ARS-sponsored research was also focused on developing best agronomic practices that minimize the adverse impacts of agriculture on the environment. ARS-sponsored climate change research projects made significant progress during the past five years towards achieving these goals. The research approach has emphasized

- developing fundamental data sets at a variety of locations across the U.S., and at a variety of spatial and temporal scales that are representative of diverse U.S. agricultural eco-regions,
- combining laboratory, plot, field and landscape studies to understand the spatial and temporal nature of contributing factors/processes,
- short-term and long-term experiments to understand the temporal response of the agricultural ecosystems to the environmental forces,
- use of existing data collection tools and the development of innovative measurement technologies such as remote sensing commensurate with the scale of problems under study,
- developing and using of process models to understand the contributions of multiple stresses (i.e. air, water, soil and agronomic practices) on agricultural ecosystems performance,
- developing standards and protocols for collecting, processing and sharing of observations and models among interdisciplinary teams of researchers across geographic locations throughout U.S.

Notable examples of specific outcomes from these projects include:

- basic knowledge of soil C and N properties and processes that are critically important to sustainable production, and reduction of GHG emissions from agricultural systems,
- basic knowledge of the consequences of enhanced atmospheric CO_2, increasing air temperatures, and decreased water availability on crop production, crop nutritional quality, pressure from weeds and invasive species,
- models that can be used for further scientific inquiry into different global change scenarios and their impact on agricultural ecosystems, for tactical decision-making by producers and land managers, and for establishment of environmental and agricultural policies,
- measurement tools for quantifying environmental states and processes at a variety of spatial scales, which can be used for assessments of C storage and cycling as SOM and crop residues in agricultural ecosystems,
- an understanding of plant traits and attributes that are most suitable for coping with environmental stresses and taking advantage of advanced genomics and genetics for breeding plant varieties most suitable for anticipated climatic conditions.

ARS is poised as a leader in the field of global change research to help understand the impacts of global change on agriculture, enable agriculture to adapt to global change and reduce the impact of agriculture on factors affecting global change. The research conducted for the 2002 through 2007 time period has set the stage for future directions of ARS global change research. The completion of this five year cycle of research coincides with global climate change reports issued by the IPCC and the CCSP, domestic and international discussions on global warming, and an increased awareness of climate change issues. Future research is expected to place greater emphasis on adaptation to, and coping with, global change and ways to further reduce agriculture's impact on climate.

The ARS Global Change Program's vision is for a productive and profitable future for American agriculture based on a research program that correctly anticipates changes and provides the tools for producers to adapt to change. This report serves as documentation of the efforts of ARS to make this vision a reality.

Appendix A: **Current Research Projects Contributing to ARS Global Change Research**

Research Projects Associated with National Program 204
Note: C=contributing to NP204

Location and Principal Investigator	NP Code	Project Number and Title
C.L. Walthall Beltsville, MD	204	0500-00034-001-00D Global Change Research
S. Britz Beltsville, MD	204	1235-11520-002-00D Environmental Effects on Phytochemicals in Food Crops: Connecting Global Change and Human Nutrition
G. McCarty Beltsville, MD	204 211 (C)	1265-12130-002-00D Assessing Climate, Soil, and Landscape Processes Affecting Agricultural Ecosystems
J. Bunce Beltsville, MD	204 203 (C) 302 (C)	1275-11210-001-00D Crop and Weed Responses to Increasing Atmospheric Carbon Dioxide
D. Timlin Beltsville, MD	207 204 (C)	1275-61660-004-00D Mechanistic Process-Level Crop Simulation Models for Research and On-Farm Decision Support
D. Douds Wyndmoor, PA	202 204 (C) 302 (C)	1935-12000-010-00D Development of Efficient and Practical Methods for Producing Arbuscular Mycorrhizal Fungi
D. Stott W. Lafayette, IN	202 211 (C) 204 (C)	3602-12220-006-00D Impact of Soil Resource Management on Soil Biochemical and Chemical Processes
D. Ort Urbana, IL	302 204 (C)	3611-21000-020-00D Identifying and Manipulating Determinants of Photosynthate Production and Partitioning
T. Sauer Ames, IA	204 202 (C)	3625-11000-004-00D Trace Gas Exchanges in Midwest Cropping Systems
D. Laird Ames, IA	202 211 (C) 204 (C)	3625-11120-003-00D Biogeochemical Processes Influencing Formation and Stabilization of Soil Organic Matter and Soil Structure
J. Baker St. Paul, MN	202 204 (C)	3640-12000-007-00D Farming Practices for the Northern Corn Belt to Protect Soil Resources, Support Biofuel Production and Reduce Global Warming Potential
J. Johnson Morris, MN	204 202 (C) 305 (C)	3645-11000-003-00D Soil Carbon Cycling, Trace Gas Emission, Tillage and Crop Residue Management
S. Papiernik Morris, MN	202 204 (C)	3645-12610-001-00D Soil and Crop Management Systems to Sustain Agricultural Production and Environmental Quality in the Northern Great Plains

B. Kimball Maricopa, AZ	204	5347-11000-008-00D Predicting Interactive Effects of CO2, Temperature and Other Environmental Factors on Agricultural Productivity
J. Smith Pullman, WA	202 204 (C) 207 (C)	5348-11120-004-00D Soil Conservation Systems for Sustainability of Pacific Northwest Agriculture
H. Collins Prosser, WA	207 204 (C) 304 (C)	5354-21660-001-00D Sustainable Potato Cropping Systems for Irrigated Agriculture in the Pacific Northwest
S. Wuest Pendleton, OR	202 204 (C) 207 (C)	5356-11120-002-00D Soil Conservation Systems for Sustainability of Pacific Northwest Agriculture
R. Follett Ft. Collins, CO	204 202 (C)	5402-11000-007-00D Interactions Between Land Use, Land Mgmt, and Climate Change: Relations to Carbon and Nitrogen Cycling, Trace Gases and Agroecosystems
A. Halvorson Ft. Collins, CO	202 211 (C) 204 (C)	5402-12130-008-00D Improving Soil and Nutrient Management Systems for Sustained Productivity and Environmental Quality
J. Morgan Cheyenne, WY	204 202 (C) 205 (C)	5409-11000-003-00D Global Change: Responses and Management Strategies for Semi-Arid Rangelands
B. Weinhold Lincoln, NE	202 204 (C) 211 (C)	5440-12210-050-00D Soil Management Systems for Dryland and Irrigated Cropping Systems
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