

CLR Activity Plan
NP 204 - Global Change
January 2006 – March 2006

CRIS Project Number

5402-11000-007-00D

Research Management Units

Lead scientists units:

5402-07 [Soil Plant Nutrient Research](#) Laboratory
3645-05 North Central Soil Conservation Research Laboratory
3625-15 National Soil Tilth Laboratory
5348-25 [Land Management and Water Conservation Research](#)

Locations

Ft. Collins, Colorado
Morris, Minnesota
Ames, Iowa
Pullman, Washington

Cross-Location Research Project (CLR). See attached table (Appendix A) for all locations involved.

Title

GRACEnet (Greenhouse Gas Reduction through Agricultural Carbon Enhancement network): An assessment of soil carbon sequestration and greenhouse gas mitigation by agricultural management

Investigators

Lead scientists:

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See attached table (Appendix A) for list of all participants.

Scientific Staff Years:

10.55

Planned Duration: 60 months

Pre-Peer Review Signature Page

(SIGNATURE AND DATES MUST BE COMPLETE PRIOR TO DISTRIBUTING THIS PROJECT PLAN TO PEER REVIEWERS)

Ronald F. Follett, 5402-11000-007-00D GRACEnet, (Greenhouse Gas Reduction through Agricultural Carbon Enhancement network): An assessment of soil carbon sequestration and greenhouse gas mitigation by agricultural management

This project plan was found to meet the peer review criteria, to be in compliance with the Project Plan Instructions and Format, and demonstrate how the research team will conduct research in a manner appropriate for this area of research. The funds committed toward this project are sufficient to support the planned research.

Research Leader

Date

This project plan was prepared by a qualified research team and demonstrates the research team's best effort towards achieving the assigned research objectives.

Center, Institute or Lab Director

Date

This project plan was prepared by a qualified research team and demonstrates the research team's best effort towards achieving the assigned research objectives. All internal review and approval requirements have been met. This project plan is relevant to the Agricultural Research Service's National Program [enter NP # and title] Action Plan and was prepared in accordance with the outlined objectives, experimental approach, and project duration previously agreed to by the National Program Team and Research Team. To validate the plan's readiness for implementation and gain recommendations for improvement, the project plan is now available for peer review.

Area Director

Date

These officials have not performed a scientific merit peer review. Their statements do not necessarily require expertise in the scientific subjects associated with this research. The approval to implement this project plan cannot be made without scientific peer review coordinated by the Office of Scientific Quality Review, ARS, USDA.

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PROJECT SUMMARY

Global climate change is a natural process that currently appears to be strongly influenced by human activities, which increase atmospheric concentrations of greenhouse gases (GHG) in particular carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Agriculture contributes about 20% of the world's global radiation forcing from CO₂, CH₄ and N₂O, and produces 50% of the CH₄ and 70% of the N₂O of the human-induced emission. Changes in management including minimizing or eliminating tillage, adding organic matter (e.g. cover crops, manure), improving nitrogen management for enhanced efficiency can convert agriculture from a net source to a net sink of GHG. There is increasing interest among land managers, policy makers, GHG emitting entities, and carbon (C) brokers in using agricultural lands to sequester C and reduce GHG emission. Precise information is lacking, however, on how specific management practices in different regions of the country impact soil C sequestration and the mitigation of GHG emission. The GRACENet (Greenhouse gas Reduction through Agricultural Carbon Enhancement network) represents a coordinated national effort by the Agricultural Research Service to provide information on the soil C status and GHG emission of current agricultural practices, and to develop new management practices to reduce net GHG emission and increase soil C sequestration primarily from soil management. The emphasis is on comparing among common management scenarios at each location. The soils, crops and condition will be location specific, but consistent methods and detailed record keeping will be used to facilitate cross-location comparison and to ensure quality control.

OBJECTIVES

1. Evaluate the soil C status and direction of change of soil C in existing typical and alternative agricultural systems.
2. Determine net GHG emission (CO₂, CH₄ and N₂O) of current agricultural systems in existing typical and alternative agricultural systems.
3. Determine the environmental effects (water, air and soil quality) of the new agricultural systems developed to reduce GHG emission and increase soil C storage.

Note: All participating units will address objective 1. Those units with the capacity to measure trace gases will also address objective 2. While those with the capacity to measure other environmental parameters will also address objective 3. See Appendix A; scenarios 1 and 2 correspond to objective 1, scenario 3 corresponds to objective 2 and scenario 4 corresponds to objective 3.

NEED FOR RESEARCH

Description of Problems to be Solved -

Global climate change is a continuously occurring natural process that currently appears to be strongly influenced by human activities including agriculture. The human influence is primarily from activities that increase atmospheric concentrations of GHG, in particular carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Agriculture contributes about 20% of world's global radiation forcing from CO₂, CH₄ and N₂O. Agriculture produces 50% of the CH₄ and 70% of the N₂O of the human-induced emission of these gases. However, changes in management including minimizing or eliminating tillage, adding organic matter (e.g. cover crops, manure), improving nitrogen management for enhanced efficiency can convert agriculture from a net source to a net sink of GHG. Recent estimates indicate that U.S. soils have the potential to sequester 220 Tg C y⁻¹. There is increasing interest for this type of research within both customer and non-customer groups, including farmers, ranchers and other land managers, policy makers, GHG emitting entities, and carbon (C) brokers in using agricultural lands to sequester C and reduce the emission of CO₂, CH₄ and N₂O. Precise information is lacking, however, on how specific management practices in different regions of the country impact soil C sequestration and the mitigation of GHG emission. This information is a prerequisite for the widespread adoption of C credit trading. Furthermore, this information, which will likely be region-specific in the U.S., needs to be generated and summarized. In addition, efforts to inventory current agricultural emission and predict future emission through the application of mathematical models will require additional data. The GRACENet (**G**reenhouse gas **R**eduction through **A**gricultural **C**arbon **E**nhancement **n**etwork) represents a coordinated effort by the Agricultural Research Service to provide information on the soil C status and GHG emission of current agricultural practices, to develop new management practices to reduce net GHG emission and to increase soil C sequestration primarily from soil management. As discussed later in this document, the anticipated products include development of: (1) A national database of GHG flux and C storage, (2) Regional and National guidelines of management practices that reduce GHG intensity, (3) Evaluation of computer models to assess management effects, and (4) Summary papers for use by action agencies and policy makers.

Relevance to ARS National Program Action Plan -

This research contributes directly to the ARS Global Change Program National Program. In particular, this project will contribute to the Carbon Cycle and Carbon Storage and Trace Gases Problem Areas. Specifically, this project contributes to the following products in the 204 action plan: i) management systems that improve nutrient utilization and limit GHG emission from cropping systems, pastures and rangelands; ii) decreased agricultural GHG emission; iii) seasonal and annual prediction capability for the various gases; and iv) improved national inventories of trace gases. It is also relevant to the Soil Resource Management National Program action plan in addressing the Soil Carbon, Conservation Systems and Nutrient Management Problem Areas.

Potential Benefits Expected from Attaining Objectives –

Assessment and improvement of soil and agricultural management will provide information to producers, scientists, action agency personnel, C traders policy makers and ultimately the general public that can be used to quantify agriculture's impact on GHG emission. More importantly, means to mitigate GHG while simultaneously improving soil quality will be developed. This a high profile activity because of its contributions to the priorities of the USDA Global Change Office, the Climate Change Science Program (e.g., the North American Carbon Project) and the Climate Change Technology Program.

SCIENTIFIC BACKGROUND

The primary objectives of GRACENet are to identify and develop agricultural strategies that will enhance soil C sequestration and reduce GHG emission and to provide a scientific basis for possible C credit and trading programs, which can be used to reduce net emission of GHG and improve environmental quality. This program will generate information on C storage in agricultural systems, which is needed by producers, program managers, and policy makers. Scenarios evaluated in GRACENet will not only address mitigation of carbon dioxide (CO₂) emission through soil C sequestration, but also their effects on N₂O and CH₄. Both grazing lands (range and pasture) and croplands (irrigated and dryland) will be investigated. The information generated will be applicable at the local (e.g., farm or ranch), regional and national scales. GRACENet's geographical extent, use of common procedures, and cooperation with other North American Carbon Cycle research programs will result in robust information to promote scientifically based conservation technologies that are relevant to national and international policy makers, as well as to agricultural producers and practitioners (Jawson et al., 2005).

Global concentrations of GHG in the atmosphere have increased measurably over the past 250 years. Carbon dioxide, CH₄, and N₂O concentrations in the atmosphere have increased by roughly 31, 151, and 17 percent, respectively since 1750 (IPCC, 2001). Currently land use change is the second largest global cause of CO₂ emission, while CO₂ from burning fossil fuels is the largest contributor (IPCC, 2001). Agriculture and forestry practices contribute GHG to the atmosphere through land use conversions, cultivation and fertilization of soils, production of ruminant livestock, and management of livestock manure. Management of agricultural lands has helped offset GHG emission by promoting the biological uptake of CO₂ through the incorporation of C into biomass, wood products, and soil. Land use and land use change can be managed to rebuild C stocks in soil and biomass with the potential essentially to reverse past emission from historical land use conversions (USDA, 2004).

The actual amount of C currently being sequestered in the U.S. is estimated at 8-14 Tg yr⁻¹ (Eve et al., 2002; Sperow et al., 2003). This amount is minor compared with the *potential* of soils in the U.S. to sequester C, which is projected to be ~220 Tg yr⁻¹ (Follett, 2001; Follett et al., 2001; Kimble et al., 2002; Lal et al., 1998, 2003). This difference represents a significant opportunity. Undoubtedly, potential for increased C sequestration exists worldwide. Some important considerations are the expected rate of C sequestration, possible economic benefits to producers, the ease with which producers can alter land use and management, the effects of targeting practices or regions, and policy structures to encourage C sequestration (Sperow et al., 2002).

Besides agriculture's relationship to the removal and sequestration of CO₂ from the atmosphere to within soil, its activities also emit N₂O and CH₄. Estimates of anthropogenic GHG emission from the U.S. in 2002 (USEPA, 2004; USDA, 2004) suggest that agriculture contributes 1.0 Tg of N₂O or 73% of total N₂O emission, accounting for about 4% of the total GHG emission in the U.S. (expressed as CO₂ equivalents). Small amounts are emitted from animal production and waste handling (including land application of animal wastes). Nitrous oxide is emitted during both nitrification and denitrification, but the majority occurs during denitrification (Conrad, 1995; Venterea and Rolston, 2000). Agriculture is responsible for about 7.7 Tg of CH₄ or 27 % of total CH₄ emission, accounting for about 2% of the total GHG emission in the U.S. (expressed as CO₂ equivalents) (USDA, 2004). Agriculturally derived CH₄ in the U.S. is produced primarily from animal production and manure handling and storage. Due to their abilities to trap solar radiation and their long residence time in the atmosphere, CH₄ and N₂O contribute much more than CO₂ on a molecular basis to global warming. Preventing the emission of 1 gram of CH₄ or N₂O has the same effect on the atmosphere as sequestering

about 21 and 310 grams of CO₂, respectively, based 100-year global warming potentials (IPCC, 2001). Authors of the 2001 IPCC report state that "...most of the observed warming over the past 50 years is likely to have been due to the increase in GHG concentrations." Management of these gases in agricultural settings has implications for C storage practices and policies. However, practices that decrease N₂O and CH₄ emission are also of great interest in the GRACEnet project.

Changes in management including minimizing or eliminating tillage, adding organic matter via cover crops, manure, improving nitrogen management for enhanced efficiency as well as other practices can convert agriculture from a net source to a net sink of GHG (Lal et al., 1998; Follett et al., 2001). There is increasing interest among farmers, ranchers, other land managers, policy makers, GHG emitting entities, and carbon (C) brokers in using agricultural lands to sequester C and reduce the emission of CO₂, CH₄ and N₂O. Precise information is lacking on how specific management practices in different regions of the country impact soil C sequestration and the mitigation of GHG emission (Follett et al., 2005b). This information is a prerequisite for the widespread adoption of C credit trading. Furthermore, this information, which will likely be region-specific in the U.S., needs to be generated and summarized. In addition, efforts to inventory current agricultural emission and predict future emission through the application of mathematical models will require additional data (Follett et al., 2005b).

Site-specific adaptation of appropriate conservation technologies will be needed for sequestering C and reducing N₂O emission. Adoption of improved conservation technologies to mitigate GHG emission should consider (i) the rate of C sequestration or GHG mitigation, (ii) the price offered for adopting various practices, (iii) the ease with which producers and land managers can alter land use and management activities, (iv) the potential impacts of targeting regions or practices, (v) the ancillary benefits to soil, water and air quality upon adoption of practices to sequester soil organic C or mitigate GHG emission, and (vi) the effectiveness and efficiency of various policies.

Development of improved conservation technologies to reduce GHG emission could become part of more comprehensive conservation programs aimed at environmental protection, food security, and agricultural sustainability. An overarching research need is to determine the multiple benefits and trade-offs of improved conservation technologies so that land managers can systematically meet production and environmental goals and so that the most effective policies can be devised.

The GRACEnet project represents a coordinated effort by the Agricultural Research Service to provide information on soil C status and GHG emission of current agricultural practices, and to develop new management practices to reduce net GHG emission and increase soil C sequestration primarily from soil management. This project is directly linked to the projects shown in Appendix A. Most of these projects are coded to the Global Change and Soil Resource Management National Programs. There will be close coordination among the participating ARS locations (see attached tables) and their individual CRIS projects as they contribute to this multi-location project. Although they may not be directly working on this project, it will possible to coordinate with other ARS locations that do related work because the results and research outlined in this prospectus will be made available through ARS national program planning meetings, national and regional scientific meetings, publications, and numerous personal contacts with scientists across many locations. This research will also be coordinated with related projects in USDA/CSREES in particular CASMGS (Consortium for Agricultural Soil Mitigation of Greenhouse gases) project and Department of Energy's CSiTE (Carbon Sequestration in Terrestrial Ecosystems) project.

APPROACH AND PROCEDURES

Objective 1. Evaluate the soil C status and direction of change of soil C in existing typical and alternative agricultural systems.

Hypothesis: Soil and agronomic management practices can be developed that sequester more soil C than those currently and/or typically used.

Objective 2. Determine net GHG emission (CO₂, CH₄ and N₂O) of current agricultural systems in existing typical and alternative agricultural systems.

Hypothesis: New agricultural systems can be developed that will decrease net GHG emission while increasing soil C storage.

Objective 3. Determine the environmental effects (water, air and soil quality) of the new agricultural systems developed to reduce GHG emission and increase soil C storage.

Hypothesis: The development of agricultural systems that reduce GHG emission while increasing soil C storage will also improve water, air, and soil quality.

The GRACEnet project has identified four products, which represent an integration of the objectives:

Product 1. A national database of GHG flux and C storage. All relevant project data from every network unit will be entered into a common data base for use by project scientists and others.

Product 2. Regional and national guidelines of management practices (in the form of a decision aid) that reduce GHG intensity, applicable for use by producers, federal and state agencies, and C brokers. These guidelines will be produced in consultation with the USDA Global Change office and others to insure that they are in a format to meet their needs

Product 3. Development and evaluation (e.g., IPCC) of computer models created to assess management effects on net GHG emission. GRACEnet data will be used to evaluate the adequacy of IPCC constants and models such as CQESTR, Century, Daycent, and COMET.

Product 4. Summary papers for action agencies and policy makers, based on the current state of knowledge. The information generated by GRACEnet will be used to produce a synthesis documents for action agencies such as NRCS, the USDA Global Change Program Office and other policy makers. These documents will address the feasibility of adopting the practices studied in GRACEnet and the amount of C sequestration and GHG reduction that is likely to result from their adoption as well as other issues of concern to them.

Approach:

The GRACEnet experimental concept is based on four location-specific scenarios or treatments:

1. Business as usual

What is the C accumulation rate under typical agricultural management practices?

These business as usual systems should be economically viable or at least used by the majority of producers that are able to continue in production agriculture in that area of

the country. Each unit will determine the number of sub treatments it will research, since there may be many variations on typical practices within a geographic area.

2. Maximizing C sequestration rate

What has to be done to achieve the highest rate of sequestration in that production system?

These treatments may be either economically feasible or technically feasible. The only constraint is that they remain in a agriculturally feasible production system. Each unit will determine the number of sub treatments it will research, since there will be many variations on practices to potentially maximize C sequestration.

3. Minimizing net GHG emission. This system differs from #2 because N₂O and CH₄ emission must also be considered.

How does this management scenario compare with #2? What is the sequestration rate and net GHG balance when all GHG emission are considered?

Agriculture is the main source of N₂O and CH₄ to the atmosphere. Therefore, data will be collected by the units that have the capability and capacity to determine N₂O and CH₄ on the treatments under study in scenarios 1 and 2. Practices will be developed to decrease the emission of N₂O and CH₄. Each unit that addresses this scenario will determine the number of sub treatments it will research, since there will be many variations on practices to potentially maximize C sequestration.

4. Maximizing environmental benefits. Carbon sequestration may well become part of a larger conservation benefit package. Land managers and policy makers will be interested in tradeoffs among management options.

With careful management, how can soil C sequestration and GHG emission be balanced with water quality, air quality, and soil quality goals?

Units capable of evaluating environmental benefits and C sequestration will be encouraged both to study the individual issue or issues that they can address (water quality, air quality, or soil quality goals) and to collect data that may contribute information that is consistent with the needs of the 'larger conservation benefit package' that may be implemented by USDA or other action agencies.

Economically viable management practices that are typical of an area (business as usual scenario), including for major crop(s), tillage practice(s) and inputs provide a basis to evaluate the C status and direction of change of soil C stocks. Depending upon resources and in addition to scenarios 1 and 2, units will address treatments 3 and/or 4. See Appendix A for each unit's treatments. Common protocols are being used for soil sampling, plant measurements, trace gas sampling and micrometeorological measurements (Appendix B-E); these protocols are accessible through a shared GRACEnet site. Reference soil and gas samples will be sent to each laboratory for quality control and assurance purposes.

Contingencies – The goal of this project is to compare current and alternative farming systems with regard to soil C sequestration and net GHG emission. Failure to demonstrate differences in C sequestrations and/or net GHG emission within the first year will be the result of three possibilities: 1) insufficient time has lapsed for the treatments to be expressed and within the sensitivity of measurement methods, 2) meaningful differences do not actually exist, or 3) variability is too high to allow for determination of existing differences. If some practices are found to be significantly better than others, additional research will be developed to: i) develop a mechanistic understanding of the reasons for the success, and ii) modify the successful practice

to improve economic viability and increased effectiveness in reducing GHG emission. However, if real differences in management practices are not observed over the five-year term of this project, this too, will be valuable information.

PHYSICAL AND HUMAN RESOURCES

See appendix A and parent CRIS project plans.

PROJECT MANAGEMENT AND EVALUATION

GRACEnet was developed through a series of workshops and conference calls. Annual workshops are planned to exchange data, address issues and concerns (e.g. common protocols, data exchanges, QC/QA). Subgroups have been established to review common protocols. Currently a shared website has been established for posting protocols, data files or other documents. Participants will also communicate via email and conferences calls.

MILESTONES AND OUTCOMES

Project Title	GRACEnet (Greenhouse Gas Reduction through Agricultural Carbon Enhancement network): An assessment of soil C sequestration and greenhouse gas mitigation by agricultural management		Project No.	5402-11000-007-00D
Product/ outcome	1. Database of soil C and trace gas flux for crop, pasture and rangeland systems in the U.S. Database will be a valuable asset for: i) scientists investigating agricultural practices on C sequestration and trace gas flux, ii) for model development and testing, and iii) a foundation for Products 2, 3, 4 of this plan.			
Performance Measure	5.2.2: Develop agricultural practices that maintain or enhance soil resources, thus ensuring sustainable food, feed, and fiber production while protecting environmental quality. 5.2.4: Develop agricultural practices and decision support strategies that allow producers to take advantage of beneficial effects and mitigate adverse impacts of global change. 5.2.6: Develop agricultural and decision support systems that assist in increasing the efficiency of agricultural enterprises and achieve economic and environmental sustainability.			
Steering Team	Steve DelGrosso; Tim Parkin, Dave Archer, Jeff White, Jason Gross, Brett Runion			
Participants	All participating GRACEnet Sys (Appendix A) will contribute data to database.			
SY Team coordinators	Milestones	Progress/ Changes	Planned completion	
S. DelGrosso, T. Parkin, B. Runion, J. Johnson, R. Follett	Identify variables to be included in database (with appropriate units)		February 2006	
J. White	Draft data fair use policy statement. Distribute to steering committee.		February 2006	
S. DelGrosso	Identify form and location of interim data depository (TRAGnet/Sharepoint)		March 2006	
S. DelGrosso, T. Parkin, J. Johnson, J. Smith, R. Follett	Develop draft spreadsheet template. Distribute to Product 1 steering committee and Lead Scientists for comment. Make necessary modifications.		April 2006	
D. Archer, J. Gross	submit pilot data sets for database testing. Test database using at least two sites (including representatives from both crop and grazing land)		May 2006	
T. Parkin, D. Archer, J. White, J. Gross, B. Runion, S. DelGrosso	Test data submission, data sharing, and data query functions		June 2006	
S. DelGrosso, T. Parkin	Develop final spreadsheet template and database protocols. Distribute to GRACEnet participants.		July 2006	
All GRACEnet Participants	Submit data annually		September/ annually	
J. White, S. DelGrosso	Review database structure and assess functionality, remodeling and other applications annually. Modify if necessary.		Dec. 2006	
S. DelGrosso	Granted data base access to the public.		2009	
Product/ outcome	2. Regional and national publications and guidelines of management that reduce GHG intensity, applicable for use by producers, federal and state agencies and C brokers.			
Steering Team	Jeff Smith, Ardell Halvorson, Hal Collins, Mayssoon Mikha, Jack Morgan, Dale Westerman, Lewis Ziska, Dolen Morris.			
SY Team coordinators	Milestones¹	Progress/	Planned	

		Changes ^l	completion
J. Smith, A. Halvorson, H. Collins, M. Mikha, J. Morgan, D. Westerman, L. Ziska, D. Morris	Identify regions or major crops for which to develop guidelines		March 2006
J. Smith, A. Halvorson, H. Collins, M. Mikha, J. Morgan, D. Westerman, L. Ziska, D. Morris	Develop preliminary publication and guidelines from existing knowledge/data		October 2008
J. Smith, A. Halvorson, H. Collins, M. Mikha, J. Morgan, D. Westerman, L. Ziska, D. Morris	Evaluate model output results as related to preliminary guidelines/fact sheets		October 2009
J. Smith, A. Halvorson, H. Collins, M. Mikha, J. Morgan, D. Westerman, L. Ziska, D. Morris	Summarize and publish guidelines and other information based on GRACENet research results		October 2010
Product/ outcome	3. Evaluation and modification of computer models created to assess management effects on net GHG emission.		
Steering Team	Ron Follett, David Archer, Hero Gollany, Paul Doraiswamy, Bruce Kimball, Jeff White, Laj Ahuja, Steve DelGrosso		
SY Team coordinators	Milestones^l	Progress/ Changes^l	Planned completion
D. Archer, H. Kludze	Conduct predictive runs of proposed scenarios for selected GRACENet sites using EPIC and COESTR models.		May 2006
H. Gollany, P. Doraiswamy, Y. Liang	Recalibrate or modified COESTR model and initial revalidation of the model with selected sites in the Corn Belt		July 2006
D. Archer, H. Kludze	Estimate economic and environmental performance of EPIC and COESTR models.		August, 2006
D. Archer, H. Kludze	Identify tradeoffs between environmental objectives and economic returns using selected GRACENet site data.		February 2007
J. White, B. Kimball, G. Wall	Examine the feasibility of selected plant growth models* without major modification to output soil respirations as well as non-CO2 trace gases.		July 2007
H. Gollany, Yi Liang	Revalidation of Modified COESTR with a range of diverse sites throughout North America		July 2007
J. White, B. Kimball, H. Gollany	Examine the feasibility of coupling COESTR with one or more plant growth models*, either as a module within or as a linked sequence.		July 2007
P. Doraiswamy, R. Hunt, G. McCarty, R. Follett	Valid of EPIC-Century at selected sites in the Corn Belt and select counties in Virginia		July 2007
H. Gollany, R. Follett, Y. Liang	Provide predictive runs for proposed scenarios for GRACENet sites.		July 2008
B. Kimball, L. Ahuja, H. Gollany, J. White, G. Wall, P. Doraiswamy, S. DelGrosso	Evaluate and cross compare GRACENet models**, IPCC methodology, possible other methodologies (Soil Conditioning Index) for their overall performance on collected data from GRACENet sites.		July 2009
P. Doraiswamy, R. Hunt, G. McCarty	Complete and test of decision support systems (DSS) in selected GRACENet sites in the Corn Belt		July 2009
P. Doraiswamy, R. Hunt, G. McCarty	Implementation of DSS for NRCS application		July 2010
H. Gollany, S,	Distribute COESTR on CD ROMs with a program tutorial, and a		July 2010

Albrecht, R. Follett	Windows interface "help" function, and train ARS scientists interested in using the model.		
Product/ outcome	4. Summary paper for action agencies and policy makers based on the current state of knowledge		
Steering Team	Jane Johnson, Alan Franzluebbbers, Mark Liebig, Diane Stott, Michel Cavigelli, Curtis Dell		
SY Team coordinators⁹	Milestones¹	Progress/ Changes¹	Planned completion
A. Franzluebbbers, J. Johnson, M. Liebig, R. Follett, M. Jawson, D. Stott	Prepare executive summary based on extended 2005 review papers		November 2006
J. Hatfield, A. Franzluebbbers, M. Cavigelli	Highlight GRACEnet results at USDA-Symposium on Natural Resource to offset Greenhouse Gas Emission meeting in 2007 -		March 2007
D. Stott, A. Franzluebbbers, M. Liebig	Prepare and submit special group publication of meeting presentations for publication in peer review journal		November 2008
D. Stott, C. Dell	Highlight GRACEnet results at USDA-Symposium on Natural Resource to offset Greenhouse Gas Emission in 2009		March 2009
M. Cavigelli, C. Dell, D. Stott, J. Johnson, R. Follett, T. Parkins, J. Smith	Prepare and submit summary paper –based on special issue plus additional publications and database information		November 2010

* Plant Growth Models included are CSM, *ecosys*, and GLYSIM.

**GRACEnet models include the following process based computer models: CQESTR, EPIC-Century, CSM, *ecosys*, GLYSIM, DAYCENT, RZWQM, as well as an evaluation of IPCC methodologies.

Communications: Periodic meetings (at least annually) of team members, with additional communication by telephone, e-mail, and sharepoint.

ACCOMPLISHMENTS FROM PRIOR PROJECT PERIOD

This is the first official project plan for GRACENet. GRACENet was first put forth as a concept during the NP204, Global Change workshop, 2002. A USDA-ARS workshop held in September 2002 organizing GRACENet activities at least 20 locations were represented at the workshop. The workshop focused on information sharing, logistics for sampling analysis, data management, and QA/QC. It was during this workshop that the four scenarios were discussed and formalized. Another outcome of the service workshop was the establishment of working groups to prepare drafts of the standard guidelines for sampling (e.g., trace gas and soil samples). In March 2003, a trace-gas training workshop was held. The focus of this workshop was to train researchers and their support staff on construction and use of closed-vented chambers, methods for handling trace gases, data management and QA/QC.

One of the products of 2002 service workshop was a special issue of Soil and Tillage Research (Volume 83, issue 1). The goals of that publication were to (1) assemble a database on agricultural management effects on soil C sequestration and GHG emission, (2) synthesize what is known and identify what is not known about the effects of agricultural management on GHG emission and mitigation potential in different regions of North America, (3) determine major ecoregion differences in how agricultural management might mitigate and contribute to GHG emission, and (4) present future research needs (Franzluebbers and Follett, 2005). This issue features six review papers (Follett et al., 2005a; Franzluebbers, 2005; Gregorich et al., 2005; Johnson et al., 2005; Liebig et al., 2005; Martens et al., 2005) and a model analysis of soil N₂O and GHG flux (Del Grosso et al., 2005).

LITERATURE CITED

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- Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima. 2005. DAYCENT model analysis of past and contemporary soil N₂O and net greenhouse gas flux for major crops in the USA. *Soil Tillage Res.* 83:9-24.
- Eve, M.D., Sperow, M., Paustian, K., Follett, R.F., 2002. National-scale estimates of changes in soil carbon stocks on agricultural lands. *Environ. Poll.* 116:196-204.
- Follett, R. F., 2001. Soil management concepts and carbon sequestration in cropland soil. *Soil Tillage Res.* 61:77-92.
- Follett, R., J.Z. Castellanos, and E.D. Buenger. 2005a. Carbon dynamics and sequestration in an irrigated Vertisol in Central Mexico. *Soil Tillage Res.* 83:148-158.
- Follett, R.F., Kimble, J.M., Lal, R., 2001. The potential for U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. Lewis Pub. Boca Raton, FL, 442 p.
- Follett, R.F., S.R. Shafer, M.D. Jawson, and A.J. Franzluebbers. 2005b. Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA. *Soil Tillage Res.* 83:159-166.
- Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil Tillage Res.* 83:120 -147.
- Franzluebbers, A.J., and R.F. Follett. 2005. Greenhouse gas contributions and mitigation potential in agricultural regions of North America: Introduction. *Soil Tillage Res.* 83:1-8.
- Gregorich, E.G., P. Rochette, A.J. VandenBygaart, and D.A. Angers. 2005. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil Tillage Res.* 83:53-72.
- IPCC. 2001. *Climate Change 2001: The Scientific Basis.*
<http://www.grida.no/climate/ipcc_tar/wg1/index.htm>.
- 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. *Soil Tillage Res.* 83:167-172.
- 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 Tillage Res.* 83:73-94.
- Kimble, J.M., Lal, R., Follett, R.F., 2002. Agricultural practices and policies for carbon sequestration in soil. Lewis Pub. Boca Raton, FL, . 512 p.
- Lal, R., Follett, R.F., Kimble, J.M., 2003. Achieving soil carbon sequestration in the United States: A challenge to the policy makers. *Soil Sci.* 168:827-845.
- Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V., 1998. The potential of US cropland to sequester carbon and mitigate the greenhouse effect. Lewis Pub. Boca Raton, FL, 128 p.
- Liebig, M.A., J.A. Morgan, J.D. 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 Res.* 83:25-52.
- 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 Tillage Res.* 83:95-119.
- Sperow, M., Eve, M., Paustian, K., 2003. Potential soil C sequestration on U.S. agricultural soils. *Climatic Change* 57:319-339.
- USDA. 2004. *US Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001.* Global

- Change Program Office, Office of the Chief Economist , U.S. Department of Agriculture. Technical Bulletin No. 1907. 164 p. <http://www.usda.gov/oce/gcpo>.
- USEPA, 2004. The EPA 2004 Inventory of U.S. Greenhouse Gas Emissions and Sinks. <http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsNational.html>.
- Venterea, R.T., and D.E. Rolston. 2000. Mechanisms and kinetics of nitric and nitrous oxide production during nitrification in agricultural soil. *Global Change Biology* 6:303-316.

PAST ACCOMPLISHMENTS OF INVESTIGATOR(S)

Past Accomplishments – Ronald F. Follett

Title: Research Leader/Supervisory Soil Scientist

Address: Soil-Plant-Nutrient Research Unit, USDA-ARS

Bldg. D, Suite 100, 2150 Centre Ave,

Fort Collins, CO 80526

Ph: 970-492-7220; Fax: 970-492-7213; Email: Ronald.Follett@ars.usda.gov

Education:

1957-1961 Colorado State University

BS degree in Soil Science

1961-1963 Colorado State University

MS degree in Soil Science

1963-1966 Purdue University

PhD degree in Soil Science

Professional Experience:

1986 to Present: USDA-ARS-SPNRU, Research Leader, Fort Collins, CO.

1976 to 1986: USDA-ARS-NPS, National Program Leader for Soil Fertility, Stripmine Reclamation and Environmental Quality, Beltsville, MD and Fort Collins, CO.

1975 to 1976: USDA-ARS, Cornell Univ. and the US Soil Plant Nutrition Lab, Ithaca, NY.

1968 to 1975: USDA-ARS, Research Soil Scientist, Mandan, ND.

1966 to 1968: First Lieutenant and Captain; Research Branch of the US Army Artillery and Missile School in Fort Sill, OK.

Selected Professional, Advisory/Outreach Activities:

Chair of Division S-4 (Soil Fertility) and on the Board of Directors of the Soil Science Society of America (SSSA), and as 1992/1993 and 2005/2006 President of the CO Chapter of the Soil and Water Conservation Society (SWCS). He has authored or coauthored over 200 scientific contributions, including organizing and serving as lead editor of six books, co-author on one book and co-editor on another 5 books, all that deal with environmental quality issues. He is a frequent invited speaker or poster presenter at local, regional, and national meetings. The book on Nitrate and Ground Water Quality has been distributed nationally within USDA and it and the NLEAP computer model in the book are used by NRCS in every state to help them address ground water quality and nitrate. It has sold over 2000 copies. His books on soil C sequestration, especially the book on C Sequestration in US Cropland Soils has sold over 3000 copies and is used widely by policy makers and scientists alike.

Research Activities:

Dr. Follett has a long record of demonstrated accomplishments and is recognized nationally and internationally for his research on soil C and nitrogen research. He has co-authored or edited/co-edited a total of 12 books, been a leader in the development and use of stable isotopic research techniques under field conditions, and developed methodology whereby the natural stable isotopic labels of C4 (warm season) and C3 (cool season) plants can be used to follow and begin to understand soil C sequestration processes. Dr. Follett has also been a leader in the development of technology to understand the processes whereby nitrate-N from agricultural sources leaches into groundwater supplies and to aid in the development of technology whereby such losses can be decreased and N use efficiency can be increased. His leadership through his personal research, publication of books, holding workshops, has encouraged numerous scientists to conduct research on the topic of managing N to protect the environment.

Total Career Publications: refereed journals (80); books authored (1); books edited (11); book chapters (45); proceedings (40); popular articles (7); films for TV (1); abstracts (80); and other (11).

Twenty Selected Publications (past 10 years) [Follett R. F.]:

- Leavitt, S.W., **R.F. Follett**, and E.A. Paul. 1996. Estimation of slow- and fast-cycling soil organic carbon pools from 6N HCl hydrolysis. *Radiocarbon* 38: 231-239.
- Porter, L.K., **R.F. Follett**, and A.D. Halvorson. 1996. Plant N-15 uptake in a wheat-sorghum-fallow-wheat sequence under no-till in the semi-arid Great Plains. *Agron. J.* 88:750-757.
- Follett, R.F.**, E.A. Paul, S.W. Leavitt, A.D. Halvorson, D.Lyon, and G.A. Peterson. 1997. Carbon isotope ratios of Great Plains soils in wheat-fallow systems. *Soil Sci. Soc. Am. J.* 61:1068-1077.
- Paul, E.A., **R.F. Follett**, S.W. Leavitt, A. Halvorson, G. Peterson, and D. Lyon. 1997. Determination of the pool sizes and dynamics of soil organic matter: Use of carbon dating for Great Plains soils. *Soil Sci Soc Amer J.* 61:1058-1067.
- Hunter, W.J., **R.F. Follett**, and J.W. Cary. 1997. Use of vegetable oil to stimulate denitrification and remove nitrate from flowing water. *Trans. Am. Soc. Ag. Eng.* 40:345-353.
- Amelung, W., W. Zech, X. Zhang, **R.F. Follett**, H. Tiessen, E. Knox, and K. Flach. 1998. Carbon, nitrogen, and sulfur pools in particle-size fractions as influenced by climate. *Soil Sci. Soc. Am. J.* 62:172-181.
- Lal, R., **R.F. Follett**, J.M. Kimble, and C.V. Cole. 1999. Management of U.S. cropland to sequester carbon in soil. *J. Soil Water Conserv.* 54:374-381.
- Follett, R.F.**, S.E. Samson-Liebig, J.M. Kimble, E.G. Pruessner, and S.W. Waltman. 2001. Carbon sequestration under the Conservation Reserve Program in the historic grassland soils of the United States of America. p. 27-40. In R. Lal (ed.) *Soil Carbon Sequestration & the Greenhouse Effect*. SSSA Sp. Pub. 57. SSSA, Madison, WI. 236 p.
- Follett, R.F.** 2001. Innovative ¹⁵N microplot research techniques to study nitrogen use efficiency under different ecosystems. *Commun. Soil Sci. Plant Anal.* 32:(7&8):951-979.
- Follett, R.F.** 2001. Soil management concepts and carbon sequestration in cropland soils (ISTRO Keynote paper, Fort Worth, TX; July 3-5, 2000). *Soil Tillage Res.* 61:77-92.
- Follett, R.F.**, J.M. Kimble, and R. Lal. (eds). 2001. *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*. Lewis Publishers, A CRC Company, Boca Raton, FL. 442 p.
- Follett, R.F.** and J.A. Delgado. 2002. Nitrogen fate and transport in agricultural systems. *J. Soil Water Conserv.* 57:402-408
- Eve, M. D., M. Sperow, K. Paustian, and **R. F. Follett**. 2002. National-scale estimation of changes in soil carbon stocks on agricultural lands. *Environ. Pollut.* 116:431-438.
- Halvorson, A. D., **R F. Follett**, M. E. Bartollo, and F. C. Schweissing. 2002. Nitrogen fertilizer use efficiency by furrow irrigated onion and corn. *Agron. J.* 94:442-449
- 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.
- Qian, Y.L. and **R. Follett**. 2002. Assessing carbon sequestration in turfgrass soil using long-term soil testing data. *Agron. J.* 94:930-935.
- Lal, R., **R.F. Follett**, and J.M. Kimble. 2003. Achieving soil carbon sequestration in the U.S.: A challenge to the policy makers. *Soil Sci.* 168:827-845.
- Follett, R.F.**, J.M. Kimble, S. Leavitt, and E. Pruessner. 2004. The potential use of soil C isotope analyses to evaluate paleoclimate. *Soil Sci.* 169:71-488.
- Delgado, J.A., M.L. Dillon, R.T. Sparks, and **R.F. Follett**. 2004. Tracing the fate of 15N in a small-grain potato rotation to improve accountability of N budgets. *J. Soil Water Cons.* 59:271-276.
- ***Follett, R.F.**, J.Z. Castellanos, and E.D. Buenger. 2005. Carbon sequestration in a Vertisol in Mexico. *Soil Tillage Res.* 83:148-158.
- * Indicates publications derived from this research.

Past Accomplishments of Jane M-F Johnson

Education:

- 1995 University of Minnesota, Plant Biology Ph.D.
 1990 University of Minnesota, Soil Science M.S.
 1983 University of Minnesota, Morris Biology major, Chemistry minor, B.A.

Experience:

- | | |
|--------------|---|
| 1988-1992 | Graduate Research Assistant, Soil Science Department University of Minnesota, St Paul, MN |
| 1992-1993 | Scientist, Soil Science Department, University of Minnesota, St Paul, MN |
| 1993-1995 | Graduate Research Assistant, Department of Soil, Water and Climate, University of Minnesota, St. Paul, MN |
| 1995-1996 | Post Doctoral Scientist, Department of Soil, Water and Climate, University of Minnesota, St Paul, MN |
| 1996-2000 | Assistant Professor, Biology Department, joint appt. with Soil Division, College of Natural Resources, University of Wisconsin, Stevens Point, WI |
| 2000-2004 | GS-12, Agricultural Scientist, USDA-ARS, Morris, MN |
| 2004-Present | GS-13, Agricultural Scientist, USDA-ARS, Morris, MN |

Accomplishments:

Demonstrated that application of corn stover fermentation by-product to eroded soil stabilizes soil structure and that long-term corn stalk removal may not be sustainable due to potential increases in erosion and potential for accelerated loss of soil organic matter. **Role:** Served as lead scientist on DOE reimbursable account (\$30.5K, 2003), one of six ARS research units conducting research on the environmental and production consequences of removing corn stover from the field. **Impact:** DOE has incorporated the environmental risk in a preliminary complete life-cycle analysis of using corn stover as a biofuel. Work highlighted in CSA news the newsletter for members of Crop Science Society of America, Soil Science Society of America, and American Society of Agronomy; resulted in ARS News and Events Press release.

Preserving soil quality assures maintenance of soil productivity to provide food and fiber for society in an environmentally sound manner. **Role:** Summarized, interpreted, and prepared the microbial biomass C and N sections of a manuscript dealing with cropping system effects on soil biological properties as a team member of the Soil Quality Group of the Great Plains Cropping System Network. **Impact:** Presented results were at the Dynamic Cropping System Symposium, an invited poster session of the 2003 ASA annual meeting, and submitted for a special issue of Renewable Agriculture and Food Systems. **Role:** Serves as one of four co-leaders assigned to coordinate writing GRACEnet CLEAR, and organizing and moderating 2005 GRACEnet workshop, Fort Collin, CO. Lead author on review article to assess current state of knowledge on trace gas emission in Central US. Article published in a special edition of Soil and Tillage Research and presented at national meeting. Conducts trace gas sampling in selected treatments of plots, in second of three-year data collection. **Impact:** The review work identified of current estimates of carbon storage potential and greenhouse gas emission estimates from the Central US, and identification of important knowledge gaps and related research needs. National data base of trace gas emission from agricultural systems is being generated and systems which minimize negative environmental impact identified.

Publications [Johnson, J M-F.]:

- Voorhees, W.B., **J.F. Johnson**, G.W. Randall, and W.W. Nelson. 1989. Corn growth and yield as affected by surface and subsoil compaction. *Agron. J.* 81:294-303.
- Johnson J.F.**, D.L. Allan, and C.P. Vance. 1994. Phosphorus stress-induced proteoid roots show altered metabolism in *Lupinus albus*. *Plant Physiol.* 104:657-665.
- Johnson J.F.**, D.L. Allan, C.P. Vance, and G. Weiblen. 1996. Root carbon dioxide fixation by phosphorus-deficient *Lupinus albus*: contribution to organic acid exudation by proteoid roots. *Plant Physiol.* 112:19-30.
- Johnson J.F.**, C.P. Vance, and D.L. Allan, 1996. Phosphorus deficiency in *Lupinus albus*: Altered lateral root development and enhanced expression of phosphoenolpyruvate carboxylase. *Plant Physiol.* 112:31-41.
- Uhde-Stone, C., G.A. Gilbert, **J.M.F. Johnson**, R. Litjens, K.E. Zinn, S.J. Temple, C.P. Vance, and D.L. Allan. 2003. Acclimation of white lupin to phosphorus deficiency involves enhanced expression of genes related to organic acid metabolism. *Plant Soil* 248:99-116
- Kern, C. C., Friend, A. L., **Johnson J.M.F.**, and Coleman, M. D. 2004. Fine-root dynamics in a developing *Populus deltoides* plantation. *Tree Physiol.* 24:651-660.
- 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 review of the literature. *Agron. J.* 96:1-17
- Johnson J.M.F.**, Reicosky D, Lindstrom M, Sharratt B, and Voorhees W. 2004. Soil characterization after amending soil with the by-product of corn stover fermentation. *Soil Sci. Soc. Amer. J.* 68:139-147
- ***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 Tillage Res.* 83:73-94.
- Pikul, J.L., **J.M.F. Johnson**, S.F. Wright, T. Caesar, and M. Ellsbury. 2005. Soil organic matter and aggregate stability affected by tillage, p. 243-258, *In* G. E. A and G. Davies, eds. Humic substances: Molecular details and applications in land and water conservation. Taylor and Francis, New York, NY.
- ***Johnson, J.M.F.**, R.R. Allmaras, and D.C. Reicosky. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agron. J.* in press (accepted October 28, 2005).

* Indicates publications derived from this research.

Past Accomplishments of Tim Parkin

Education:

1980 University of Wisconsin - Madison, Bacteriology/Water Chemistry; Ph.D.

1978 University of Wisconsin - Madison, Bacteriology; M.S.

1976 Wabash College, Biology; B.A.

Experience:

1980-1983 Post doctoral research Associate, Department of Plant and Soil Sciences, Michigan State University, East Lansing, MI. Responsible for research on methods development for quantifying soil denitrification.

1983-1990 Research Microbiologist, USDA-ARS, Soil Nitrogen and Environmental Laboratory, Beltsville, MD. Responsible for research on soil N transformations as related to nitrate contamination of groundwater. This work included identification of environmental controls of microbial N processes and investigations of spatial variability of these processes. Participated in collaborative work on microbial degradation of pesticides.

1990-2002 Research Microbiologist, USDA-ARS, National Soil Tilth Laboratory. Responsible for conducting research on soil nutrient cycling and water quality. Responsible for conducting research on microbial activity and soil quality.

2002-present Research Leader, USDA-ARS, Air Quality of Agricultural Systems Research Unit, National Soil Tilth Laboratory, Ames, IA. Responsible for development of research program dealing with agricultural impacts on air quality, including programs examining ammonia, H₂S, and particulate emission from animal operations, development of methods for assessing transport of contaminants in air, and assessment of cropping systems with respect to net greenhouse gas emission.

Accomplishments:

Soil C and N Transformations. This work investigated microbial populations and activities in relation to the activities of other organisms (earthworms and plants) and the resulting impact on soil C and N cycling reactions. New methods were developed to estimate fungal biomass to differentiate the activities of filamentous microorganisms in soil and to assess microbial secession and N regulation of C mineralization. Added N was found to stimulate C mineralization rate in the short term, but in long-term total C mineralized was not affected, indicating that N turnover may be the critical factor controlling C storage in soils. Living plants were found to stimulate net N mineralization; however, this effect was dependant upon past cropping history, suggesting strategies for improving the N supplying capacity of soils.

Trace Gas Flux from Soil. Inhibitors were evaluated with regard to distinguishing CH₄ consumption and production activities. Methods for assessing trace gas flux from soil were compared and the production and consumption of CH₄ from agricultural and non-agricultural soils was measured, and the Bowen ratio method was found to be applicable only when high fluxes are present. N₂O flux associated with poultry manure application to soil and in swine manure lagoons was quantified. Natural ecosystems were generally net consumers of atmospheric CH₄, but agricultural systems were highly variable, exhibiting both production and consumption. Specific agricultural practice (i.e. tillage/fertility) was less important than landscape position and climatic factors in determining the direction and magnitude of CH₄ flux.

Twenty Selected Publications (past 10 years [Parkin, T.B.]):

- Doran, J.W., and **T.B. Parkin**. 1996. Quantitative indicators of soil quality: A minimum data set. pp. 25-38. *In*: J.W. Doran and A.J. Jones (eds.) *Methods for Assessing Soil Quality*. Soil Sci. Soc. Am. Publication No. 49. Soil Sci. Soc. Am., Madison, WI.
- Karlen, D.L., **T. B. Parkin** and N.S. Eash. 1996. Use of soil quality indicators to evaluate conservation reserve program sites in Iowa. pp. 345-355. *In*: *Methods for Assessing Soil Quality*. Soil Sci. Soc. Am., Madison, WI.
- Parkin, T.B.**, J.W. Doran and E. Franco-Vizcaino. 1996. Field and laboratory tests of soil respiration. pp. 231-245 *In*: J.W. Doran and A.J. Jones (eds.) *Methods for Assessing Soil Quality*. Special Publication No. 49. Soil Sci. Soc. Am., Madison, WI.
- Bragan, R.J., J.L. Starr, and **T.B. Parkin** 1997. Shallow groundwater denitrification rate measurement by acetylene block. *J. Environ. Qual.* 26:1531-1538.
- Bragan, R.J., Starr, J.L., and **T.B. Parkin** 1997. Acetylene transport in shallow groundwater for denitrification rate measurement. *J. Environ. Qual.* 26:1524-1530.
- Hadas, A., **T. B. Parkin** and P.Stahl. 1998. Reduced CO₂ release from wheat straw under N-limiting conditions: Simulation of carbon turnover. *European J. Soil Sci.* 49:494.
- Chan, A.S., J.H. Prueger, and **T. B. Parkin** 1998. Comparison of closed-chamber and Bowen-ratio methods for determining methane flux from peatland surfaces. *J. Environ. Qual.* 27:232-239.
- Cambardella, C.A., T.B. Moorman, D.B. Jaynes, J.L. Hatfield, **T.B. Parkin**, W.W. Simpkins, and D.L. Karlen, 1999. Water quality in Walnut Creek Watershed: Nitrate-nitrogen in soils, subsurface drainage water, and shallow groundwater. *J. Environ. Qual.* 28:25-34.
- Parkin, T.B.**, and E.C. Berry. 1999. Microbial nitrogen transformations in earthworm burrows. *Soil Biol. Biochem.* 31:1765-1771.
- Stahl, P.D., **T.B. Parkin** and Christensen, M. 1999. Fungal presence in paired cultivated and uncultivated soils in central Iowa. *Biol. Fert. Soils* 29:92-97.
- Chan, A.S.K., and **T.B. Parkin** 2000. Evaluation of potential inhibitors of methanogenesis and methane oxidation in a landfill cover soil. *Soil Biol. Biochem.* 32:1581-1590.
- Harper, L.A., R.R. Sharpe, and **T.B. Parkin** 2000. Gaseous nitrogen emissions from anaerobic swine lagoons: ammonia, nitrous oxide, and dinitrogen gas. *J. Environ. Qual.* 29:1356-1365.
- Malpassi, R.N., T.C. Kaspar, **T.B. Parkin**, C.A. Cambardella, and N.A. Nubel, 2000. Oat and rye root decomposition effects on nitrogen mineralization. *Soil Sci. Soc. Am. J.* 64:208-215.
- Arnold, S., **T.B. Parkin**, J.W. Doran, and A.R. Mosier, 2001. Automated gas sampling system for laboratory analysis of CH₄ and N₂O. *Commun. Soil Sci. Plant Anal.* 32:2795-2807.
- Chan, A.S.K., and **T.B. Parkin** 2001. Effect of land use on methane flux from soil. *J. Environ. Qual.* 30:786-797.
- Chan, A.S.K., and **T.B. Parkin** 2001. Methane oxidation and production activity in soils from natural and agricultural ecosystems. *J. Environ Qual.* 30:1896-1903.
- Parkin, T.B.**, T.C. Kaspar and C.A. Cambardella 2002. Oat plant effects on net N mineralization. *Plant Soil.* 243:187-195.
- Parkin, T.B.**, and T.C. Kaspar. 2003. Temperature controls on diurnal carbon dioxide flux: Implications for estimating soil carbon loss. *Soil Sci. Soc. Am. J.* 67:1763-1772.
- Russell, A.E., C.A. Cambardella, J.J. Ewel, , and **T.B. Parkin**. 2004. Species, rotation, and life-form diversity effects on soil carbon in experimental tropical ecosystems. *Ecol. Applic.* 14:47-60.
- Parkin, T.B.**, and T.C. Kaspar. 2004. Temporal variability of soil carbon dioxide flux: effect of sampling frequency on cumulative carbon loss estimation. *Soil Sci. Soc. Am. J.* 68:1234-1241.

Past Accomplishments of Jeffrey L. Smith, Soil Scientist*Education:*

1983 Washington State University, Soil Chemistry/Biochemistry; PhD
1980 Washington State University, Soils; MS
1976 University of California, Soils and Plant Nutrition; BS

Experience:

1985-present Soil Biochemist, Land Management and Water Conservation Unit, USDA-ARS, Pullman, WA
1983-1985 Specialist, Department of Plant and Soil Biology, University of California, Berkeley, CA
1978-1983 Research Assistant, Department of Agronomy and Soils, Washington State University, Pullman, WA

Accomplishments:

Developed mathematical procedure for estimating non-linear N mineralization processes.
Developed multivariable geostatistical procedure for use in risk assessment and soil quality analysis.
Developed N budget for shrub-steppe ecosystems.
Developed predictive model for estimating N₂O flux from agricultural management practices and native grasslands.

Publications for J.L. Smith:

- Mummey, D.L., **J.L. Smith** and G. Bluhm. 1998. Assessment of alternative soil management practices on N₂O emissions from U.S. agriculture. *Agric., Ecosyst. Environ.* 70:79-87.
- Metting B.F., **J.L. Smith** and J.S. Amthor. 1999. Science needs and new technology for soil carbon sequestration. *In: Carbon sequestration in soils: science, monitoring and beyond.* Battelle Memorial Press, OH.
- Smith, J.L.** 1999. Transformation of organic matter and its effect on nutrient reserves. *In: Nutrient Dynamics of Tropical Banana Ecosystems.* Earth University, San Jose, Costa Rica.
- Brejda, J., T. Moorman, **J.L. Smith**, D. Karlen and A. Tao. 2000. Distribution and variability of surface soil properties at regional scale. *Soil Sci. Soc. Am. J.* 64:974-982
- Mummey, D.L., **J.L. Smith** and G. Bluhm. 2000. Model estimation of nitrous oxide emissions from U.S. grasslands. *Environ. Manage.* 25:169-175.
- Smith, J.L.** and H. Bolton Jr. 2000. Carbon sequestration in a semi-arid ecosystem. pp. 1250-1255. *In Catania (ed) Energy 2000: The beginning of a new millennium.* Las Vegas, Nevada, USA.
- Brejda, J., M. Mausback, J.J. Goebe, D.L. Allen, T. Dao, D. Karlen, T. Moorman and **J.L. Smith.** 2001. Estimating surface soil organic carbon content at a regional scale using the national resource inventory. *Soil Sci. Soc. Am. J.* 65:842-849.
- Metting B. F., **J.L. Smith**, J. S. Amthor and R. C. Izaurralde. 2001. Science Needs and New Technology for Increasing Soil Carbon Sequestration. *Clim. Change* 51:11-34.
- Smith, J. L.**, H. Bolton Jr. and J. J. Halvorson 2002 Soil properties and microbial activity across a 500 m elevation gradient in a semi-arid environment. *Soil Biol. Biochem.* 34:1749-1757.
- Bailey, V. L., **J.L. Smith**, and H. Bolton, Jr. 2002. Fungal-to-bacterial ratios in soils investigated for enhanced C sequestration. *Soil Biol. Biochem.* 34:997-1007.
- Bailey, V. L., A.D. Peacock, **J.L. Smith**, and H. Bolton, Jr. 2002 Relationships between soil microbial biomass determined by chloroform fumigation-extraction, substrate induced respiration, and lipid extraction *Soil Biol. Biochem.* 34:1385-1389.
- Ersahin, S., R.I. Papendick, **J.L. Smith**, C.K. Keller, and V.S. Manoranjan. 2002. Macropore transport of bromide as influenced by soil structure differences. *Geoderma* 108:207-223.
- Bailey, V. L., **J.L. Smith** and H. Bolton Jr. 2003. Novel antibiotics as inhibitors for the selective respiratory inhibition method of measuring fungal:bacterial ratios in soil. *Biol. Fertil. Soils* 38:154-160.
- Bell, J.M., **J.L. Smith**, V.L. Bailey and H. Bolton Jr. 2003. Priming effect and C storage in semi-arid no-till spring crop rotations. *Biol. Fertil. Soils* 37:237-244.
- Link, S.O., **J.L. Smith**, H. Bolton Jr. and J.J. Halvorson. 2003. A reciprocal transplant experiment within a climatic gradient in a semi-arid shrub-steppe ecosystem: effects on bunchgrass growth and reproduction, soil carbon, and soil nitrogen. *Glob. Change Biol.* 9:1097-1105.

HEALTH, SAFETY, AND OTHER ISSUES OF CONCERN STATEMENTS

Will be addressed in each individual project plan.

- Animal Care: This statement is not relevant.
- Endangered Species: This statement is not relevant.
- National Environmental Policy Act: On the basis that this federal project is being conducted for the sole purpose of conducting research. This project is categorically excluded in accordance with regulations for the National Environmental Policy Act.
- Human Study Procedure: This statement is not relevant.
- Laboratory Hazards: All hazardous materials will be handled with appropriate protective clothing and/or eye wear and used in fume or biological hoods as required. All pipetting is done mechanically. Appropriate hearing protection will be utilized as needed. Following the standard protocols as established at each unit.
- Occupational Safety & Health: Safety courses, training, and protective clothing and equipment are provided at respective units as needed. Following the standard protocols as established at each unit.
- Recombinant DNA Procedures: This statement is not relevant.
- Homeland Security: will follow location protocols for securing ARS assets.
- Intellectual Property Issues: no anticipated; will contact technology transfer specialist if any proprietary materials or methods are to be used and to investigate protection of any patentable technology developed.

APPENDICES

Appendix A - Participating Locations contributing data to the data based from one or more of the scenarios as represented within the respective parent CRIS. Scenarios 1 and 2 correspond to objective 1, scenarios 3 correspond to objective 2 and scenario 4 corresponds to objective 3.

Location / Unit / Mode Code	SY (% time on this project)	Parent Project Number	Parent Project Title	Scenarios/ Treatments Investigated
Akron, CO Central Plains Resources Management Research 5407-30	Maysoon Mikha (0.1) and Merle Vigil (0.1)	5407-12130-004-00D	Dryland Cropping Systems Management for the Central Great Plains	1,2,3
Ames, IA National Soil Tilth Laboratory 3625-15	Tim Parkin* (0.5) and Jerry Hatfield (0.1)	3625-11000-004-00D and 3625-11120-002-00	Trace Gas Exchanges in Midwest Cropping Systems and Biogeochemical Processes Influencing Soil Structure and Organic C Sequestration	1,2,3,4
Auburn, AL National Soil Dynamics Laboratory 6420-05	Stephen Prior (0.1), G. Brett Runion (0.05) and Kip Balkcom (0.1)	6420-11120-005-00D and 6420-12610-002-00D	Global Change and Belowground Processes in Agricultural Systems and Conservation Systems Research for Improving Environmental Quality and Producer Profitability	1,2,3
Beaver, WV Appalachian Farming Systems Research 1932-61	Katherine O'Neill (0.2)	1932-61000-002-00D	Management of Appalachian Soil Resources	1,2
Beltsville, MD Sustainable Agricultural Systems Laboratory 1265-04	Michel Cavigelli (0.2)	1265-21660-002-00D	Long-Term Field Experiment to Evaluate Sustainability of Organic and Conventional Cropping Systems	1,2,3

Beltsville, MD Hydrology Remote Sensing Laboratory and Animal Manure Byproducts Laboratory 1265-06	Paul Doraiswamy (0.15), Greg McCarty (0.2) and Jim Reeves (0.2)	New Project	New Project	1,2,3,4
Beltsville, MD Crop Systems & Global Change Laboratory 1275-51	Jim Bunce (0.1) and Lew Ziska (0.1)	1275-11210-001-00D	Crop and Weed Responses to Rising Atmospheric C Dioxide	1,2
Brookings, SD Crop & Entomology Research 5447-05	Mike Lehman (0.3) and Shannon Osborne (0.1)	5447-12620-001-00D	Integrated Soil, Crop and Pest Management for Sustainable Agriculture	1,2,3
Canal Point, FL Sugarcane Production Research 6625-05	Dolen Morris (0.2)	6625-12130-001-00D	Managing Microbial Processes of Soil Subsidence in Histosols for Sustainable Sugarcane Yield	1,2
Florence, SC Costal Plain Soil, Water and Plant Conservation Research 6657-08	Jeff Novak (0.2)	6657-12000-004-00D	Soil Management Systems for the Responsible Use of Natural Resources	1,2

Fort Collins, CO Soil Plant & Nutrient Research 5402-07	Ron Follett * (0.4) and Ardell Halvorson (0.2)	5402-11120-NEW- 00L and 5402-11000-007- 00D and 5402-12130-007- 00D	GRACEnet (Greenhouse Gas Reduction through Agricultural C Enhancement network): An Assessment of Greenhouse Gas Mitigation by Agricultural Management and Interactions Between Land Use, Land Mgmt, and Climate Change: Relations to Carbon and Nitrogen Cycling, Trace Gases and Agroecosystems and Improving Soil and Nitrogen Management Systems for Sustaining Land and Water Quality	1,2,3,4
Fort Collins, CO Rangeland Resources Research 5409-25	Justin Derner (0.2), Jack Morgan (0.1) and Jean Reeder (0.1)	5409-11000-003- 00D	Global Change: Responses and Management Strategies for Semi- Arid Rangelands	1,2, 4
Gainesville, FL Crop Genetic & Environmental Research 6615-10	L. Hartwell Allen (0.1)	6615-11000-007- 00D	Impacts of Rising Atmospheric CO2 and Temperature on Crop Growth, Reproductive Processes, Yield, and Seed Quality	1,2
Kimberly, ID Northwest Irrigation & Soils Research 5368-20	Jim Entry (0.05) and Bob Sojka (0.05)	5368-12000-005- 00D	Improving Soil Resource Management for Irrigated Agricultural Systems	1,2
Lincoln, NE Soil & Water Conservation Research 5440-10	Gary Varvel (0.1)	5440-12210-008- 00D	Soil Health as an Indicator of Sustainable Management	1,2,4
Lubbock, TX	Ted Zoebeck	6208-12000-008-	Management of	1,2

Cropping Systems Research Lab 6208-05	(0.1) and Verinice Acosta-Martinez (0.1)	00D	Sustainable Agricultural Systems That Effectively Use Water & Reduce Wind Erosion	
Mandan, ND Natural Resources Management Research 5445-20	Mark Liebig (0.2 SY) and Scott Kronberg (0.1 SY)	5445-21000-008-00D	Integrated Forage, Crop, and Livestock Systems for Northern Great Plains	1,2,3,4
Maricopa, AZ U.S. Water Conservation Laboratory 5344-20	Bruce Kimball (0.1) and Jeffrey White (0.1)	5344-11000-008-00D	Predicting interactive effects of CO ₂ , Temperature, and Other Environmental Factors on Agricultural Productivity	1,2,
Morris, MN Soil Management Research 3645-05	Jane Johnson* (0.6), Don Reicosky (0.5), Sharon Lachnicht (0.1) and David Archer (0.1)	3645-11000-002-00D and 3645-61660-001-00D	Soil Carbon Cycling, Tillage and Crop Residue Management and Cropping Systems Management to Promote Economic and Environmental Sustainability	1,2,3
Orono, ME New England Plant, Soil, & Water Research Laboratory 1915-05	Wayne Honeycutt, (0.2) and Tim Griffin (0.2)	1915-62660-001-00D	Sustainable Cropping Systems for the Northeast	1,2
Pendelton, OR Soil & Water Conservation Research 5356-05	Hero Gallony (0.4) and Steve Albrecht (0.1)	5356-12000-007-00	Sustainable Crop and Soil Management Systems for Dryland Pacific Northwest Agriculture	1,2,3
Prosser, WA Vegetable & Forage Crop Production Research 5354-10	Hal Collins (0.2)	5354-13610-003-00D	Sustainable Potato Cropping Systems for Irrigated Agriculture in the Pacific Northwest	1,2,3
Pullman, WA Land Management & Water Conservation Research 5348-25	Jeff Smith* (0.4) and Dave Huggins (0.15)	5348-11120-002-00D	Enhancing Sustainability Through Conservation Cropping Systems for PNW Agroecosystems	1,2,3,4

Sidney, MT Northern Plains Agricultural Research Laboratory 5436-05	Upendra Sainju (0.1), Jay Jabro (0.05) and Bart Stevens (0.05)	5436-13210-004-00	Ecologically-Sound Pest, Water and Soil Management Strategies for Northern Great Plains Cropping Systems	1,2
St. Paul, MN Soil & Water Management Research 3640-20	John Baker (0.2), Rodney Venterea (0.2) and Ed Clapp (0.1)	3640-12000-005- 00D	Soil and Water Management to Enhance Natural Resources and Optimize Production	1,2,3,4
Temple, TX Grassland, Soil & Water Research Laboratory 6206-05	Ken Potter (0.2)	6206-11120-003- 00D	Sustainable Soil and Crop Management Systems for Clay Soils	1,2
Tifton, GA Southeast Watershed Research Laboratory 6602-05	Tim Strickland (0.2) and Dana Sullivan (0.2)	6602-12610-004- 00D and 6602-13000-019- 00D	Soil Resources in the Coastal Plain: Process Characterization, Management Impacts & Assessment Tools and Impact of Land Use on Hydrologic and Environmental Processes for Watersheds in the Coastal Plain	1,2,4
Tucson, AZ Southwest Watershed Research Laboratory 5342-45	Dean Martens (0.2)	5342-13610-007- 00D	Hydrologic Processes, Scale, Water Resources and Global Change for Semiarid Watershed Management"	1,2,3
University Park, PA Pasture Systems & Watershed Research Management Research 1902-05	Curtis Dell (0.2), Paul Adler (0.05), Howard Skinner (0.1) and Al Rotz (0.05)	1902-21000-006- 00D	Biodiversity Management in Northeastern Grazing Lands	1,2,3,4
Watkinsville, GA Southern Piedmont Conservation Research 6612-09	Ron Sharpe (0.2) and Alan Franzluebber s (0.1)	6612-12000-011- 00D	Enhancing Soil-Water- Nutrient Processes in Southern Piedmont Pasture and Crop Systems	1,2,4
West Lafayette, IN National Soil Erosion Laboratory 3602-15	Diane Stott (0.2) and Doug Smith (0.2)	3602-12220-004- 00D	Soil Erosion and Soil Resource Management	1,2,3,4

Wyndmoor, PA Microbial Biophysics and Residue Chemistry Research Unit 1935-25	David Douds (0.1) and Jerry Nagahashi (0.1)	1935-12000-007- 00D	Monoxenic and Axenic Cultivation of Arbuscular Mycorrhizal (AM) Fungi	1,2
Total SYs and Funding	10.55 * Lead scientists			

Appendix B. Soil Sampling Guidelines*

Steering committee: Jeff Smith, Mark Liebig, Ron Follett, Gary Varvel, Verlan Cochran, Don Reicosky, Jim Reeves, Jerry Schuman, Hero Gollany, Ken Potter, Ray Allmaras, Wayne Honeycutt,

Assume spatial independence of soil properties and thus use a random sampling pattern. Record GPS coordinates of each sampling location and collect samples using a core method compositing a minimum of 8 cores per depth. If soil property variability is known the number of cores for compositing can be adjusted. As a rule of thumb biological soil properties have a spatial coefficient of variation (%CV) of >50%, chemical properties 25 to 45% and physical properties 15 to 40% depending upon the scale of sampling.

The required depth increments for GRACenet sampling are 0-5 and 5-10 cm. These depths will tend to show increases in soil C and thus would be considered a minimum data set. Preferred sampling depth increments are 0-5, 5-10, 10-20, 20-30, 30-60, 60-100 cm. If near-surface stratification is not present depth increments of 10 cm to 30 cm for the third and beyond samples are adequate. During soil sampling an assessment of surface residues should be made, the mass should be determined over a 0.25 m² area.

A suggested mass of soil of at least 500g should be collected from each depth for the initial i.e. time zero sampling. Future soil sample mass can be adjusted for the assessments being conducted. The timing and frequency of sampling will be system dependent.

Soil samples should be kept cool in the field and during transport. Samples should be maintained at 4^oC as much as possible during processing. First sieve each soil sample through a 2 mm sieve and remove a sample for gravimetric water content.

Soil Assessments

For the required and optional soil property measurements we will use standard methods of analysis. There are several references listed at the end of this document that can be consulted for proper procedures and step-by-step instructions.

Required measurements

- Soil organic C (combustion)
- Soil inorganic C
- Particulate organic matter C
- Soil bulk density
- Total N
- Extractable NH₄-N and NO₃-N
- Extractable P and K
- Soil pH (water)
- Electrical conductivity
- Particle-size distribution (initial sampling)

Optional measurements

- Soluble organic C (required if there is drainage in the system)

Microbial biomass C and N
 Water-stable aggregates
 Total C by mid/near infrared method (Jim Reeves)
 Moisture release curve

Soil Sampling Protocol Discussion items (Developed from the October 2005 GRACEnet workshop in Fort Collins, CO):

- Soil depth increments. Increments suggested in current protocol for studies being established. On-going long-term studies with different depth increments should not change sampling scheme to correspond to GRACEnet depth increments. Depth increments sampled should encompass the depth of tillage (at least eight inch depth to include data in CQESTR). Current guidelines were set up to ensure near-surface effects of management are captured. In some cases, sampling genetic horizons at deeper depths may be more appropriate (e.g., natric horizons).
- Number of soil samples: Eight composited cores per sampling site recommended in protocol for initial sampling. However, fewer cores may be collected in certain studies where plots are small and/or treatments are not tilled.
- Frequency and timing of sampling: Beyond initial baseline sampling, frequency depends on unique attributes of management system being evaluated. The timing of sampling will depend on the investigator's knowledge of a system's variance for attributes of interest.
- Sampling management zones (row/interrow, traffic/nontraffic): Agroecosystems with controlled traffic create distinct zones within a field. Compositing an appropriate number of soil samples across different zones based on the area of each zone within a field is one approach to obtaining a representative sample.
- Sample processing: Plant materials (roots and surface residue) in soil samples need to be removed prior to analysis. Removing plant material from field-moist samples was suggested, but requires significant labor input. Once dried, soil samples should be passed through a 2 mm sieve prior to analyses. If aggregate stability measurements are to be taken, it is recommended that a separate soil sample be collected for analysis and archiving.
- Sample archiving: Archiving guidelines outlined in publication by Robertson et al. (1999) (see current protocol for full citation). Suggested amount of air-dried soil for archiving is 50 g (baseline sampling) and 10 g (previous samplings). For samples collected prior to initiation of GRACEnet, there may be a need to conduct assessments from archived samples.

Method citations for inclusion in protocol and based upon October 2005 GRACEnet workshop discussion items:

- Compliant cavity method for soil bulk density – stony and sandy soils (required measurement):
 - USDA-NRCS. 2004. *Compliant Cavity (3B3)*. p. 98-100. In: R. Burt (ed.) *Soil survey laboratory methods manual. Soil survey investigations report no. 42, version 4.0. USDA-NRCS National Soil Survey Laboratory, Lincoln, NE.*
- Particulate organic matter (required measurement):
 - Cambardella, C.A., and E.T. Elliott. 1992. *Particulate organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.*
 - Gregorich, E.G., and B.H. Ellert. 1993. *Light fraction and macroorganic matter in mineral soils. p. 397-407. In M.R. Carter (ed.) Soil Sampling Methods and Analysis. Can. Soc. Soil Sci. Lewis Publ. Boca Raton, FL.*

- Wet aggregate stability (optional measurement):
 - *Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425-442. In: Klute, A., (Ed.) Methods of soil analysis. Part 1 – Physical and mineralogical methods. 2nd ed. SSSA Book Series No. 5. SSSA and ASA, Madison, WI.*
- Soil microbial biomass (optional measurement):
 - *Jenkinson, D.S., and D.S. Powlson, 1976. The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. Soil Biol. Biochem. 8: 209-213.*
 - *Vance, E.D., P.C. Brookes, and D.S. Jenkinson. 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19:703-707.*
 - *Islam, K.R., and R.R. Weil. 1998. Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biol. Fertil. Soils. 27:408-416.*
- Guidelines for sampling forest soils
 - Kathy O'Neil (Beaver, WV) will provide.
- Guidelines for steep landscapes
 - Kathy O'Neil (Beaver, WV) will provide.

Original Methods Citations:

- Carter, M.R. (ed.). 1999. Soil sampling and methods of analysis. Lewis Publ. Boca Raton, FL.
- Doran, J.W., and A.J. Jones (ed.). 1996. Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.
- Klute, A. (ed.). 1986. Methods of soil analysis. Part 1 – Physical and mineralogical methods. 2nd ed. SSSA Book Series No. 5. SSSA and ASA, Madison, WI.
- Lal, R., J.M. Kimble, R.F. Follett, and B.A. Stewart (eds.). 2001. Assessment methods for soil carbon. Lewis Publ. Boca Raton, FL.
- Robertson et al. (ed.). 1999. Standard soil methods for long-term ecological research. Oxford Univ. Press. New York.
- Sparks, D.L. (ed.). 1996. Methods of soil analysis. Part 3 – Chemical methods. SSSA Book Series No. 5. SSSA and ASA, Madison, WI.
- Weaver et al. (ed.). 1994. Methods of soil analysis. Part 2 – Microbiological and biochemical methods. SSSA Book Series No. 5. SSSA and ASA, Madison, WI.

* GRACENet Workshop Soils Protocol Discussion (Notes and Follow-up October 7, 2005).

Appendix C: Plant Sampling Guidelines

Steering committee: Jane M-F Johnson, Ron Follett, Jack Morgan, Jean Reeder, Don Reicosky, Diane Stott, Lew Ziska, Jeff White

This document provides guide lines for sampling plants shoots and roots, with additional guidelines and references for determining plant quality.

General Plant sampling guidelines

At a minimum the plant information should give an indication of the biomass input into the system. The species (crop), cropping history planting date, row width, crop rotation, phenological stage or age at time of sampling are important metadata to be recorded. Crop grain yield, above plant biomass should be determined per unit area. Root biomass is desirable. Plant biomass should be determined by individual researchers based on the vegetation/crop sampled. Timing and frequency will be system dependent although the age and physiological stage should be recorded.

The amount of total C and N in the biomass should be determined. It is recommended that ash-free biomass be determined (NREL, 2005). Additional optional quality assessment protocols are discussed below.

Plant aboveground sampling issues for quantifying weeds

In general, most plant sampling techniques that are used for crops or native species apply equally well to invasive species. However, the patchiness of weed infestations may sometimes require slightly different approaches to select representative samples. The sampling methodology and accounting for the mass of weeds (weight/unit area) will depend upon the nature of the experimental plots and the field environment. In small plot studies, sampling could be based on the overall sampling scheme for the crop species, and then separation of the weeds from the crop. Individual weeds types should be considered, including height and perhaps distance from the row. If in a more extensive area, then a transect method might be quite satisfactory. If in a pasture or other large field, then it might be reasonable to use a random method (systematic random points). This extensive sampling could be combined with more intensive random sampling in particular areas of interest. In any case it would be necessary to know the area sampled so that scaling-up and calculation of the mass of weeds per unit area can be calculated.

Unique techniques might be required for special situations. One of these might be if the desired sampling area uniformly had either C₃ or C₄ plants present in it and the species that is considered the weed were the opposite, then bulk samples could be obtained and the delta ¹³C determined and a ratio of C₃ to C₄ plants calculated based upon stable C isotope analyses.

If the question were relative leaf area of weeds or ratio of weed to crop leaf area or if some other physiological metric were desired, then of course entirely different approaches would be required.

Plant handling

Plant material should be analyzed fresh or freeze-dried, especially if soluble compounds are to be assayed (Allen, 1989). However, an acceptable compromise is to dry the material at or below 45°C, with adequate ventilation to minimize microbial or enzymatic breakdown (Allen, 1989; NREL, 1996). After drying the material should be ground to pass through a 1 mm mesh. Determination of equivalent dry-weight at 100-105°C permits results to be expressed on dry-weight basis (Palm and Rowland, 1997). Biochemical composition varies among species, and physiological stage (Constantinides and Fownes, 1994; Heal et al., 1997) it is important to include the age or physiological stage of the material and the organs included.

ROOTS

Root sampling guidelines

Introduction:

Root plasticity and variability (spatial and temporal) together with sampling challenges make it very difficult to accurately measure root biomass. As noted by Taylor (1986) all root biomass sampling techniques (e.g. soil cores, monoliths, minirhizotron, etc.) are hampered by high variability, loss of fine root biomass, and high labor requirements. In a cropping system, the aboveground vegetative biomass and the root system represents the available organic source C inputs in the soil, unless manure or other organic amendment was applied, which adds additional inputs. Understanding the role of C translocated belowground is critical to understanding the soil C cycle. Therefore, attempting to quantify belowground biomass is desired.

Depth

Rooting depths of annual crops range from about 0.5 m to around 3.0 m (Borg and Grimes, 1986; Dardanelli et al., 1997; Merrill et al., 2002; Stone et al., 2002) in contrast to perennial root crops such as alfalfa (*Medicago sativa* L), which can reach depths of 6 m after several growing seasons (Borg and Grimes, 1986). However, most crops have the majority of the root biomass within the surface 60 cm, therefore, if resources are limited, roots cores should focus on the surface 60-cm (Allmaras and Nelson, 1971; Allmaras et al., 1975; Mitchell and Russell, 1971; Weaver, 1926).

Unlike most annual cropping systems, rangelands are characterized by heterogeneity in plant community composition. Within rangeland habitats, the plant community includes three rooting types based on depth: widely spreading, *superficially rooted* (0 to 10 cm) species such as cacti; *shallowly rooted* species such as grasses, which have the majority of their dense fibrous root systems in the upper 40 cm of the soil, although some roots usually penetrate much deeper; and *deeply rooted* species, which include shrubs, half-shrubs, and forbs with primary taproot systems often penetrating to depths >1 m but with lateral roots in the upper soil layers (Lauenroth and Milchunas, 1992). In rangelands dominated by grasses, about 75 to 80% of total root biomass is in the top 30 cm of the soil, and about 44 to 57% is in the top 10 cm (Sims et al., 1978; Jackson et al., 1996; Reeder et al., 2001).

How many cores?

Due to the heterogeneous nature of soil and the non-random and non-uniform distribution of roots; variability among samples will be high, not to mention the issue of variability among techniques. Taylor (1986) in his review of root sampling techniques estimated that to have 90% confidence 40 samples with a sample volume of cm^3 would be needed and that was in relatively uniform loess soil. Rarely is it feasible to take that number of samples; therefore, researchers need to be content with high variability.

Plant patchiness causes wide variation in root mass and distribution that occur in rangeland ecosystems (Milchunas and Lauenroth, 1989), as do differences in plant community composition associated with topography and soil type (Lauenroth and Milchunas, 1992). A stratified sampling protocol across the factors (topography and plant species) controlling spatial patterns is required (Burke et al., 1999; Reeder, 2003).

When to sample:

As with all plant parameters, it is important to record at least the age and preferably the physiological stage at the time of sampling. Ideally, it would be best to sample at peak root biomass. However, this is not necessarily well defined for all crops. Liedgens et al. (2000) utilizing minirhizotrons reported that maximum root density occurred about 10 d after pollen shed at most positions to the plant row for corn. Wheat maximum root biomass is at anthesis (Siddique et al., 1990). Root growth of soybeans also appears to reach a maximum about seed set and begin declining after seed development starts (Mitchell and Russell, 1971). Maximum root biomass or root length density is not always available in the literature, a good first guess would be sometime between flowering and seed set. Measuring at physiological maturity would likely mean some of the belowground biomass is already been lost to decomposition. Siddique et al. (1990) reported that root-to-shoot ratio declined from 0.55 at anthesis to 0.4 at maturity, thus root measurements at maturity will underestimate total root biomass. Alfalfa is a perennial species, so root development would be expected to be considerably different than annual species; both the biomass and the chemical composition will change depending on how many years since planting, and from that stand point alfalfa may be more similar to perennial than to annual species.

Wide yearly variation in root biomass is common in rangeland systems and result primarily from annual variability in climatic factors (precipitation, temperature, evapotranspiration and solar radiation) which affect net primary production and plant species composition (Reeder et al., 2001). Wide intraseasonal fluctuations in root biomass also occur. In rangelands dominated by cool season grasses, maximum root biomass usually occurs in late spring or early summer (Coupland, 1992), whereas in habitats with a large warm season grass component, maximum root mass usually occurs toward the end of the growing season. However, fluctuations in root mass relate to temperature and precipitation (Lauenroth and Whitman, 1977; Milchunas and Lauenroth, 2000), so erratic temperature and precipitation patterns can suppress or accelerate plant production and alter the time at which maximum root biomass occurs (Reeder et al., 2001).

Sampling depth and horizontal

Root sampling to 60 cm, does not capture all roots, but it is the zone of maximum root density for most species. If resources allow, sampling throughout the root-depth would be ideal. It is relatively easy to use a hand probe for sampling the surface 60 cm. Sampling likely would

require the use of a hydraulic probe. Hand probes come with wet and dry tips; it is advisable to purchase some of each. Increment the sample as resources permit.

Horizontal root distribution is not uniform; therefore, it is advisable to collect samples at several horizontal positions relative to the plant between two rows. For example in corn or soybean with 76 cm row spacing, taking a probe near a plant 1-3, 12.7, 25.4 and 38.1 cm will capture some of the horizontal distribution. Three or more subplot locations within a plot are recommended.

In narrow row crops like wheat or drilled soybeans, the four horizontal positions would be next to a plant, center of inter-row, next to the next plant and the next inter-row. This strategy also can work in alfalfa, especially if it was planted with a nurse crop like wheat or oat.

To report root density (g cm^{-3}), the volume of soil sampled must be recorded. For example using a hand probe (tube inner diameter 0.75 inches) and 12 pooled probes, the volume of soil is calculated as follows:

$$\begin{aligned} (0.75 \text{ in} / 2)^2 * \pi &= 0.441786 \text{ in}^2 \\ 0.441786 \text{ in}^2 * 24 \text{ in} &= 10.60288 \text{ in}^3 \\ 1 \text{ in}^3 &= 16.4 \text{ cm}^3 \\ 10.60288 \text{ in}^3 * 16.4 \text{ cm}^3 / \text{in}^3 &= 173.8872 \text{ cm}^3 \\ 173.8872 \text{ cm}^3 * 12 \text{ cores} &= 2087 \text{ cm}^3 \end{aligned}$$

Root storage

Store the soil cores with roots plastic bags or plastic pails, refrigerate (4°C) until they can be washed, preferably within one-week. After washing and removing non-root debris. The amount of root material from 12 pooled samples will vary dramatically among crop species.

Root washing technique

Roots can be washed from the soil with hydropneumatic elutriation as described by (Smucker et al., 1982). Commercial elutriators are available from Gillison's fabrication <http://www.gillisons.com/products.htm>. Below is a brief low budget, low tech method for root-washing.

Equipment: 2 mm sieve (8" diameter), 0.6 mm sieve (or something similar), spray nozzle on hose, sink with soil trap, plastic buckets (ice cream pails), small containers (about 250 mL capacity), tray for final cleaning, forceps, and sample bag for roots.

Preliminary cleaning

1. Put sample in plastic bucket. Crumble sample as water is added using spray nozzle. Soak sample in water for ~30 minutes, keep sample bag under bucket is an easy way to keep track of sample number. (Sometimes water can be added directly to sample in plastic bag if sample is small enough.)
2. Hand-mix the sample and pour liquid off through bigger sieve. Add water and pour off. The sieve will trap the roots; this method obviously loses some of the fine roots.
3. Dump the entire sample into sieve and wash with nozzle.
4. Place well cleaned big clumps of roots into small containers with number written on outside to keep track of the sample.
5. Wash out as much soil as possible from the bigger sieve.
6. Dump the sample from sieve back into bucket, hand mix and try to get roots out. Add water; pour liquid into sieve repeatedly until no more roots seen in sample.
7. Dispose of soil left in bucket.

8. Wash sample from bigger sieve into bucket.
9. Pour roots from bucket into smaller sieve and from smaller sieve into small container (with number from step 4).
10. Keep sample in water in small container at 4°C until final cleaning.

Final cleaning

1. Pour sample onto blue tray (10"x13"x1"deep) or Pyrex crystallizing dish with plenty of water. The idea is to be able to see the roots and pick them out of the debris.
2. Pick out roots and place on white lab towel
3. Blot roots and take wet weight into spreadsheet
4. Place roots into numbered bag and store in freezer until ready for freeze drying.
5. Freeze dry and take dry weight. (If you do not have a freeze drier, dry at 45°C). The low temperature assumes there will be analysis beyond dry weight. If there is enough root biomass, determine ash-free biomass of a small sample.
6. Determine dry weight by drying a subsample at 105°C. If no chemical analysis is to be completed, the entire sample can be dried at 105°C.
7. Determine ash-free weight at 550 to 600°C Details for determining ash-free biomass can be found at http://www.eere.energy.gov/biomass/analytical_procedures.html. (NREL, 2005).

Optional Plant quality assessment

The impact of crop residues on trace gas emission (CO_2 , N_2O) is dependent upon the quality of the residue (e.g., C:N ratio, N concentration) and the size of residue. The amount of N_2O evolved depended on the type of residue incorporated and the particle size of the residue (Ambus et al., 2001; Shelp et al., 2000). The incorporation of crop residues can provide a source of readily available C and N. Greater emission of N_2O follow incorporations of residues with low C:N ratios, such as legumes of horticultural crops as compared with cereal straw incorporations (Baggs et al., 2002). Smaller crop residue particles, allow for increased microbial attack, and thus greater production of N_2O (Ambus et al., 2001). Such residues can enhance metabolic activity and form local anaerobic zones, giving favorable sites for denitrification and contribute to "hot spots" of N_2O emission (Ball et al., 1999). Homogenous mixing of residue into soil increased the amount of N_2O released compared to applying a layer of residue in soil cylinders (Ambus et al., 2001). The quality of crop residues can alter the balance of N immobilization and mineralization, thus indirectly impacting substrate availability for N_2O formation.

The ratio of C:N is an easy parameter to measure; however, it has been shown that C:N is not sufficient for predicting decomposition (Franck et al., 1997; Gorissen et al., 1995; Palm and Rowland, 1997). Palm and Rowland (1997) recommended that lignin, soluble C (soluble sugars, (if %N > 1.8%)) soluble phenolics, total N, total P, total C, and ash-free dry weight be included in a minimum data set of parameters used to characterizing plant input quality for decomposition and soil organic matter studies.

Analytical methods

There are several approaches for characterizing residue quality. One is to use a sequential extraction scheme (Figure 1). Sequential extraction allows isolation of more specific components with a limited amount of plant material; however, it is time consuming, expensive, and has more potential for experimental error (Palm and Rowland, 1997). A second method is to do separate extractions of a limited number of components (Figure 2). For example, lignin

could be extracted without first extracting starch. Separate extraction tends to reduce the experimental error (Palm and Rowland, 1997). Another method of assessing plant quality is quantify neutral detergent fiber (NDF) and acid detergent fiber (ADF) (Van Soest and Wine, 1968; Van Soest et al., 1991), which is a common method for determining digestibility of forage crops. Protocols for determining extractives, starch, total carbohydrate by HPLC, acid-soluble lignin, acid-insoluble lignin and ash have been developed by the National Renewable Energy Laboratory (NREL) at Golden, CO, and have been accepted by the ASTM as ASTM standard test methods. These methods are available at the NREL website:

http://www.eere.energy.gov/biomass/analytical_procedures.html as standard biomass analytical procedures (Table 1). The methods at the NREL site have the advantage of being very detailed, complete with background references, step-by-step protocols and sample calculation. Currently, the methods can be downloaded free of charge. In addition this web site has a biomass feedstock composition and property database, which has information on agricultural residues, wood, herbaceous energy crops and other potential biofuel sources.

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Table 1. A partial list of protocols available at NREL for characterizing residue quality.

Component	NREL protocol	Link: http://www.eere.energy.gov/biomass/analytical_procedures.html
Total solids (biomass)	LAP-001	
Extractives	LAP-010	
Starch	LAP-016	
Carbohydrates	LAP-002	
Acid-insoluble lignin	LAP-003	
Acid-soluble lignin	LAP-004	
Ash	LAP-005	

Table 2. Additional methods for characterizing residue quality.

Component	Citation
Nonstructural Carbohydrates	(Hendrix, 1993; Martens and Frankenberger, 1991)
Soluble sugars	(Dubois et al., 1956)
Soluble C and N	(Anderson and Ingram, 1993)
Soluble phenolics	(Waterman and Mole, 1994)
Alkaline extractable phenolics	(Martens and Loeffelmann, 2002)
Neutral and acid digestible fiber	(Van Soest and Wine, 1968; Van Soest et al., 1991)

Figure 1. Schematic of separate extraction for plant residue quality parameters

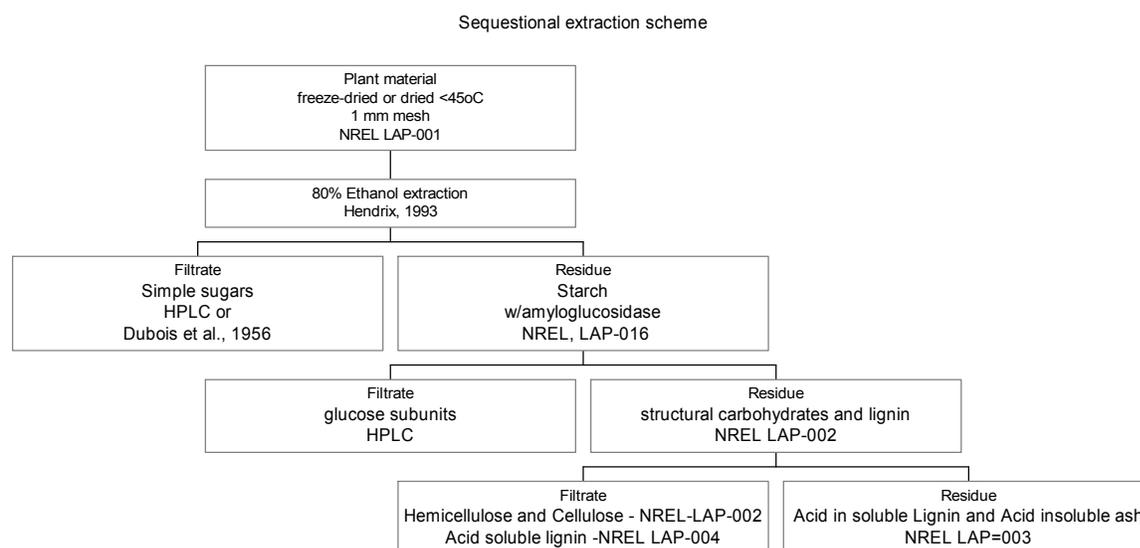
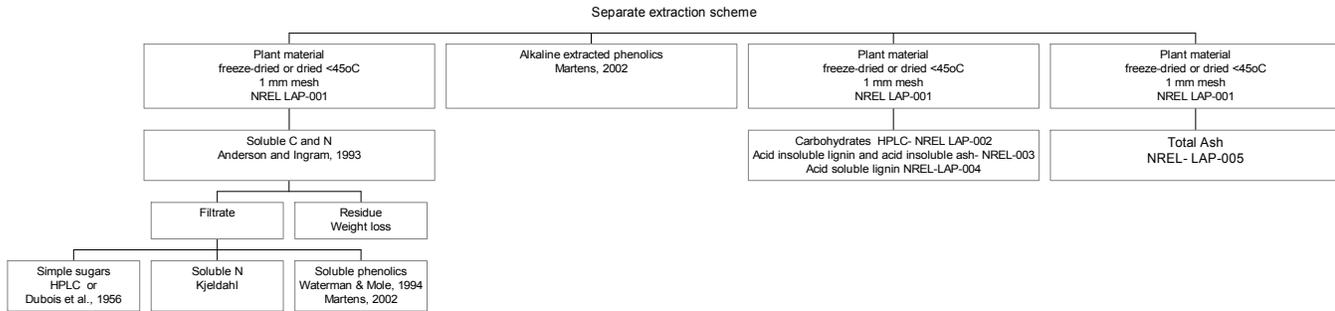


Figure 2. Schematic of separate extraction for plant residue quality parameters



Appendix D. Trace gas sampling guidelines

GRACEnet
Chamber-based Trace Gas Flux Measurement Protocol
www.GRACEnet.usda.gov April 24, 2003

Trace Gas Protocol Development Committee: Tim Parkin, Arvin Mosier, Jeff Smith, Rod Venterea, Don Reicosky, Greg McCarty, Geoffrey Doyle, John Baker

Scope:

1. This protocol only addresses N₂O and CH₄ flux measurement methodology. The reactivities of other gasses of interest such as NO_x, O₃, CO, and NH₃ will likely dictate that separate chambers and associated instrumentation be employed. CO₂ can also be included as an analyte with this protocol; however, when plants are present, interpretation of CO₂ data is complicated.

2. This protocol adopted chamber-based flux methodology (the least expensive option available) in order to allow inclusion of as many sites as possible. Since micromet techniques are expensive, they will be used at only locations with current micromet capability (e.g., Minnesota, Iowa).

3. In deciding on a chamber design, our goal was the adoption of methodology which is sensitive, unbiased, has low associated variance, and allows accurate interpolation/extrapolation over time and space. Because of our inability, at this time, to *precisely* assess the extent of bias associated with a given chamber design and sampling protocol under the range of conditions which might exist, we have adopted our 'best guess' protocol. Assessment, refinement and/or modifications of the protocol may continue in the future. At some sites this may include evaluation of chambers against micromet fluxes or performing comparisons of alternate chamber designs. Recognizing that any measurement technique will have disadvantages, the best we can do at this time is to select a technique which minimizes potential problems. To facilitate the adoption of a common technique, it is important to attain a common understanding of the potential shortcomings associated with chamber-based flux measurement techniques. The following section discusses some of these issues.

Background

Mosier (1989) reviewed the key issues related to chamber techniques for gas flux measurement. These are summarized below along with recommendations to minimize potential problems.

1. Soil Disturbance:
 - Soil disturbance upon installation
 - Longer term microclimate effects

Recommendations:

 - Use temporary/portable chambers.
 - Install permanent chamber anchors at least 24 h prior to flux determinations.
 - Minimize anchors or collars height to reduce micro environment perturbations.
 - Move chamber anchors if soil microclimate effects are observed.
2. Temperature perturbations:
 - Influence biological activity
 - May cause physical absorption or dissolution of dissolved

- gasses.
- Recommendations:*
- Use insulated, reflective chambers.
 - Keep deployment time as short as possible.
3. Pressure perturbations:
- Wind may cause pressure-induced mass flow over chamber collar.
 - Closed chamber may reduce natural mass flux.
 - Sampling effects may induce mass flow
- Recommendations:*
- Use vented chamber.
 - Use skirted chambers
4. Humidity perturbations:
- Gas solubility changes (probably a minor effect)
 - Humidity increases in the chamber may result in dilution of the gas of interest and resulting underestimate of the flux.
 - Changes in humidity may impact biological activity (minor).
- Recommendations:*
- Keep chamber deployment short.
 - Measure relative humidity changes inside chamber to correct for dilution effects from water vapor.
5. Temporal Variability:
- Diurnal variations. There is some evidence in the literature that diurnal variations (up to a factor of 10) in soil gas flux follow diurnal temperature fluctuations; however, this characterization is not consistent.
 - Daily variation. Day-to-day variation may be highly dependant upon rainfall, fertility, tillage or freeze thaw events.
 - Seasonal variation. Spring and winter fluxes can be substantial and need to be considered.
- Recommendations:*
- Measure flux at times of the day that more closely correspond to daily average temperature (mid morning, early evening).
 - Apply a temperature correction algorithm to measured fluxes when time-of-day temperature induced biases might be present.
 - Measure fluxes 3 to 4 times/week, all year long.
 - Stratify sampling to account for episodic events.
6. Spatial Variability:
- Can be extremely high. Coefficients of Variation associated with chamber-based fluxes commonly exceed 100%.
- Recommendations:*
- Use chambers with larger footprint to minimize small scale variability.
 - Use as many chambers as possible.
7. Gas Mixing:
- It is generally assumed that molecular diffusion is sufficiently rapid within the chamber headspace such that homogeneous gas concentrations exist when sampling. However, this may not necessarily be true if large amounts of vegetation are present or the chamber volume:surface area is large (Livingston and Hutchinson, 1995).
- Recommendations:*
- If it is deemed that mixing of the headspace gas is necessary, there are a couple of options.
 - 1. Chambers can be fit with small fans. A 12-VDC computer fan will run on a 9-volt transistor radio battery and is a cost-effective way of incorporating a fan into a chamber design. Computer fans

can be obtained from Action Electronics, Santa Anna, CA. Phone: (800) 563-9405, www.action-electronics.com. Example of a 12vdc fan from this company is part # 108idc12vdcs1b. Cost: ~ \$7.00 -2. A gas manifold within the chamber attached to the sampling port can be used. The manifold has a single port on one end (which extends out the top of the chamber) and multiple ports on the other end which accept narrow teflon tubing (e.g., 1/16") that extend into the chamber. The narrow tubing from each of the multiple inner ports is extended to different points inside the chamber, so that when the sample is collected, gas is pulled from multiple points in the chamber. Manifolds can be purchased from Small Parts, Inc. 800-220-4242, www.smallparts.com. An example part no. is TCM-13-20/4-10 (description = Tubing Manifold 13G inlet 20G outlet).

Given these considerations, there have been a number of different chamber-based methods proposed in the literature. Below are provided our best recommendations. See referenced literature for additional details.

Recommended Protocol

General:

Gas flux will be measured by static chambers deployed on the soil surface for a period of no more than 60 min. During chamber deployment, samples of the chamber headspace gas will be removed at regular intervals, and stored for later analysis by gas chromatography. Specific recommendations on chamber design, gas sampling and analysis, and flux calculations are provided below. Investigators are encouraged to examine the referenced literature underlying these recommendations.

Chamber design

Minimum Requirements:

1. Flux chambers should be fabricated of non-reactive materials (stainless steel, aluminum, PVC, polypropylene, polyethylene, or plexiglass.)
2. Material should be white or coated with reflective material, (mylar or painted).
3. Chambers should be large enough to cover at least 175 cm² of the soil surface, and have a target height of 15 cm (height can be decreased to increase sensitivity or increased to accommodate plants).
4. Chambers should contain a vent tube, at least 10 cm long and 4.8 mm in diameter (e.g., 1/4" stainless steel tubing). See Fig. 1 for details.
5. Chambers should have a sampling port to enable the removal of gas samples. Possible options include: butyl rubber stopper (Alltech # 95256), or nylon/polyethylene stopcock (ColeParmer # A-30600-000 : Qosina, #99705 or #99717).

Recommended Design:

Chambers have two parts; a permanent anchor, driven at least 8 cm into the soil and extending no more than 5 cm above the soil surface, and a cap which contains the vent tube and sampling port. Anchors are fabricated so that they can accommodate the flux chamber during measurement phase. Anchors and chambers were made of 20 cm (or larger) diameter PVC. Alternatively, anchors can be made of thin-walled stainless steel or aluminum to minimize physical disturbance upon insertion. The vent tube is necessary to avoid pressure perturbations (and subsequent mass flow) when chambers are installed and when gas samples are collected. Schematics of two potential chamber designs are presented and photographs of a variety of chambers in operation are provided in Appendices 3 and 4.

Chamber deployment

Anchors : As indicated above, anchors should be installed at least 8 cm into the ground and extend no more than 5 cm above the surface. Permanent anchors should be installed at least 24 h prior to first flux measurement. There are no fixed guidelines regarding how long anchors can (or should) be left in place. In cultivated systems, chamber anchors are typically removed prior to cultivation, planting, or fertilizer application, and then replaced. In grassland studies anchors have been left for over 10 years with no apparent deleterious effects. One advantage of leaving anchors in place is that soil disturbance and root damage are minimized. However, there have been reported problems with microclimate effects within the anchors left in place for extended periods. For example, changes in humidity or shading can cause algal growth, and in heavy or compacted soils ponding of rainwater can occur. This is not a desirable situation. It will be up to the investigator to determine how often chambers should be moved.

Plants:

If the goal of this project is to quantify ecosystem contributions to net trace gas flux, then ideally, plants should be included inside chambers during flux determinations. There is some information indicating that N_2O emission may be facilitated by living plants (Chang et al., 1998; Chen et al, 1999; Smart and Bloom, 2001). However, inclusion of plants presents an interesting problem. With regard to sensitivity, inclusion of plants would likely dictate that chamber height be increased, but an increase in chamber height results in a corresponding decrease in sensitivity (i.e., increase in minimum detectable limit, see below). Significant reductions in sensitivity might, in some cases, result in all the flux measurements being below the detection limit. In such cases, it is advisable to also measure bare soil fluxes (i.e. between rows in row-crop agriculture) using shorter chambers which have higher sensitivity. Results could then be reported as fluxes within a range of the bounds established by the two measurements. If it is not feasible to include plants at all growth stages, at least deploy chambers both within and between rows (in row crop agriculture). Alternatively, chambers with a larger foot print and therefore

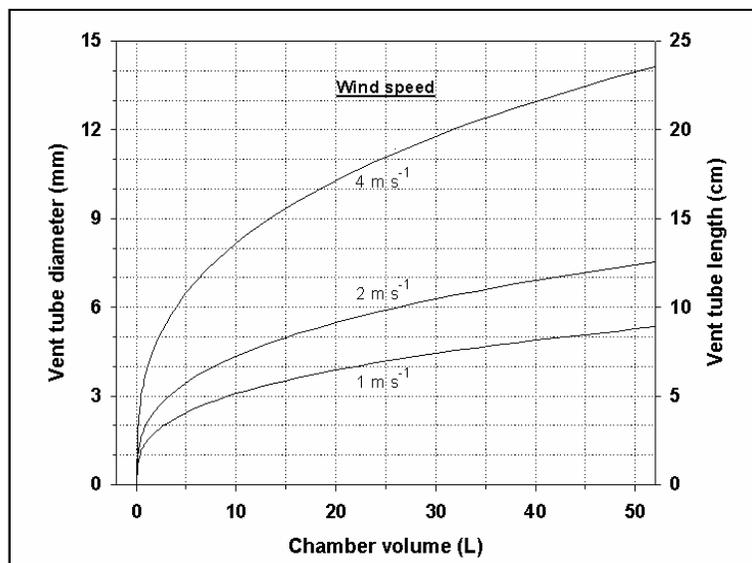


Figure 1. Optimum vent tube diameter and length for selected wind speeds and enclosure volumes as described by Hutchinson and Mosier (1981).

providing more representative coverage of the ecosystem under study can be used.

Sample numbers:

Trace gas fluxes exhibit a high degree of spatial variability; thus, the more chambers, the better. Variability may also be a function of chamber size, and may be reduced by using larger chambers. Recommendation for minimum number is two chambers per treatment in plot scale studies. In landscape or field scale studies it is recommended that 'similar' landscape elements be identified and a stratified sampling design employed, whereby samples are stratified by landscape element, soil type, or vegetation (Livingston and Hutchinson, 1995). In situations where identifiable hot spots may occur (e.g., urine patches in a grazed system) a stratified sampling may have to be developed to account for this. Gilbert (1987) gives some sampling guidelines when hot spots exist.

Sampling frequency:

Trace gas fluxes exhibit a high degree of temporal variability. Thus, the more frequently measurements are made, the better. There are several elements to temporal variability that must be considered: diel or diurnal variations, seasonal variations, and variations induced by perturbation (e.g., tillage, fertility, irrigation/rainfall, thawing). Flux measurements should be made mid-morning of each sampling day to minimize biases associated with diurnal variations. However, a Q_{10} temperature correction procedure may be applicable to adjust rates determined at different times. The temperature correction procedure assumes that temperature variations are the primary factor driving diurnal flux variations, thus the temperature correction adjusts the measured flux to the average daily soil temperature. To account for perturbation effects it is recommended that fluxes be measured as soon as possible after the perturbation (such as rainfall, tillage, or fertility event), then daily for the next several days during and following the specific event. During the remainder of the year, gas flux measurements should be made at regular time intervals (1, 2 or 3 week intervals) as resources allow.

Gas sampling

Fluxes are measured by determining the rate of change of trace gas concentration in the chamber headspace. In most cases trace gas concentrations are determined by physically removing a gas sample from the chamber headspace for analysis in the laboratory. Gas samples should be withdrawn at regular intervals during the chamber deployment. Chambers should be in place no longer than 60 minutes. The shorter time the deployment time, the better, but deployment must be long enough so that sensitivity is not compromised. At least 3 time points are required for flux calculation: time 0, and two additional points, equally spaced in time (e.g. 0, 30, 60 min. or 0, 20, 40 min). *[Note: Sampling is performed at regular intervals to facilitate flux calculation by Eq. 1 (below). However, more samples can be collected, and sampling does not have to be at regular intervals if the stochastic model of Petersen et al., (2001) is used.]* Sampling is performed by inserting a polypropylene syringe into the chamber septa and slowly removing a gas sample. Mixing of headspace gas by pumping

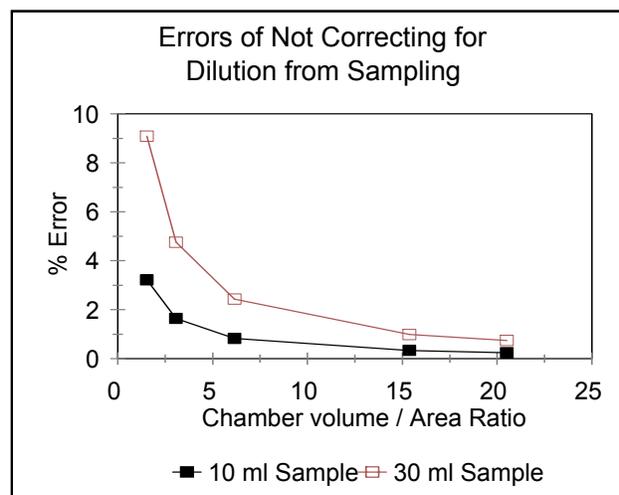


Figure 2. Percentage underestimation of flux rate due to headspace dilution as a result of sampling presented as a function of chamber geometry and gas sample size.

the syringe before sampling is not recommended as pumping may cause pressure perturbations and/or excess dilution of headspace gas by entry of outside air through the vent tube. The gas volume removed at each time point is dictated by the specific gas analysis technique to be used. Typically, from 5 to 30 ml are removed. If the syringe is equipped with a stopcock, the sample can be stored directly in the syringe. Alternatively, the gas sample can be transferred to a previously evacuated glass vial sealed with a grey butyl rubber septum. If this option is selected, excess gas is usually injected into the evacuated vial (relative to the vial volume) to produce an overpressure. This overpressure facilitates the subsequent removal of a gas sample for analysis. Brooks (1993) evaluated several storage protocols and found that red rubber stoppers such as found on commercially available evacuated blood vials were the worst. Parkin has observed that red rubber stoppers react with CH₄. However, others report no problems with coated red rubber stoppers. Details of gas sampling and analyses are noted in Mosier et al. (1991, 1996). It should be noted that each time a headspace gas sample is removed from the chamber outside, air flows into the chamber through the vent tube. This results in a dilution of the analyte in the chamber headspace. The error associated with this dilution effect is a function of both the sample volume withdrawn and the chamber Volume/Surface Area ratio (Figure 2). Correction for this dilution effect should not be necessary for chamber Volume/Surface Area ratios >10 and sample volumes < 30 ml. An example of a gas sampling protocol is presented in Appendix D2.

Gas Analysis

Samples should be run as soon as possible after collection. Gas chromatography will be used for analysis of N₂O and CH₄ (electron capture detector for N₂O and flame ionization detector for CH₄). Specific method of gas sample injection into the GC will depend upon the specific instrumentation available at each location. However, it is recommended that the GC be fit with a sample valve to minimize injection error. To account for problems associated with GC drift it is recommended that: 1) samples from individual chambers are run in sequence (e.g. t₀, t₁, t₂,) rather than segregating all the samples by time (e.g. all samples run together) and 2) standards are run periodically throughout the sample run (e.g. every 10 to 20 samples).

Standards:

Standards should be prepared each sampling time. Standards should be handled in a manner similar to samples with regard to collection and storage. Preferably samples should be prepared in the field (i.e. injected into glass vials, or collected in syringes). Several different standard concentrations should be run, as detector response may be nonlinear. The range of standards should bracket the concentrations found in samples [e.g., N₂O; 0.1, 1.0 and 10 ppm. CH₄; 0.5, 1, 2, 10 ppm). Standard curves are then used to convert the GC output of the samples into units of ppm. Certified standard gasses can be obtained from Scott Specialty Gas (www.scottgas.com) or Scott Marian.

Data Analyses:

Flux Calculation:

Fluxes are calculated from the rate of change of the concentration of the analyte of interest in the chamber headspace. Since the units associated with the gas standards are typically ppm(v), when the standard curve relationship is applied to calculate gas concentrations of the samples, the resulting unit of the analyte is also ppm(v). Volumetric parts per million (ppm(v)) has units of $\mu\text{L trace gas L}^{-1}$ total gas.

If the rate of change of headspace trace gas concentration is constant (ppm (v) vs. time data is linear), then linear regression can be used to calculate the slope of the concentration vs. time data. The slope of the line is the trace gas flux. Thus, a regression of ppm (v) vs. minutes will

result in a slope with units of ppm (v) min⁻¹. Multiplying the slope by the chamber volume (L) and dividing by the chamber surface area (m²) will result in a flux with units of uL trace gas m⁻² min⁻¹

If the rate of change of headspace trace gas concentration is not constant (ppm (v) vs. time data is curvilinear), then linear regression is not appropriate. Curvilinear concentration data with time is attributed to a build up of the analyte concentration in the chamber headspace, which alters the diffusion gradient and the resulting flux. To account for this effect, Hutchinson and Mosier (1981) proposed an algorithm as an alternative to linear regression (Eq. 1).

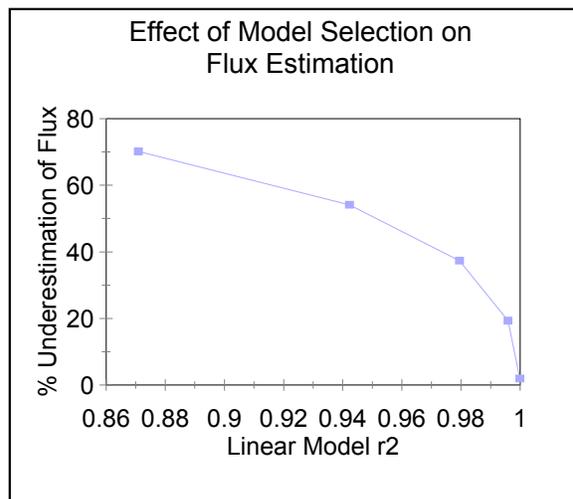
$$f_0 = V(C_1 - C_0)^2 / [A * t_1 * (2 * C_1 - C_2 - C_0)] * \ln[(C_1 - C_0)/(C_2 - C_1)] \quad \text{Eq. [1]}$$

where f_0 is the flux at time 0, V is the chamber headspace volume (L); A is the soil surface area (m²); C_0 , C_1 , and C_2 are the chamber headspace gas concentrations (ppm (v)) at time 0, 1, and 2, respectively; and t_1 is the interval between gas sampling points (min). The resulting units of f_0 are: uL trace gas m⁻² min⁻¹.

It should be noted that this correction algorithm only works if $[(C_1 - C_0)/(C_2 - C_1)] > 1$ and if time points are equally spaced.

As an alternative to Eq. 1 for calculating a flux from curvilinear data, Pedersen et al. (2001) has proposed a stochastic diffusion model. The reported advantages of the Pedersen model are: i) a more rigorous treatment of gas diffusion theory, ii) there is no requirement for equi-spaced data points, and iii) it can accommodate more than three data points, iv) it provides an assessment of goodness of fit, and v) it has a lower failure rate than Eq. 1. This technique will not be described in detail here; however, the computer model can be obtained from S.O. Petersen at Soren.O.Petersen@agrsci.dk. Regarding linear regression, it should be realized, that in deciding whether to use linear regression or a non-linear model, a strict criteria for goodness of fit should be established for the linear model. Simulation data shows that even slight deviations from linearity can have a dramatic influence on the calculated flux (Fig. 3).

Fig. 3. Percentage underestimation of flux from linear regression as compared to non-linear analysis from Eq. 1



Flux calculations from linear regression or the non-linear models described above produce values with units of $\mu\text{L trace gas m}^{-2} \text{ min}^{-1}$. An additional calculation has to be performed in order to convert flux values from a volumetric basis to a mass basis. To perform this conversion the ideal gas law must be invoked (Eq. 2)

$$PV = nRT$$

where P = pressure, V = volume, n = the number of moles of gas, R = the gas law constant, and T = temperature.

The ideal gas law quantifies the relationship between pressure, volume, mass and temperature of a gas.

Relationship between altitude and atmospheric pressure.

Alt (ft)	mm Hg	psi	atm
0	29.92	14.7	1.000335
1000	28.86	14.18	0.964949
1320	28.54	14.02	0.954061
2000	27.82	13.67	0.930244
2640	27.14	13.33	0.907107
3000	26.81	13.17	0.896219
3960	25.77	12.66	0.861513
4000	25.84	12.69	0.863555
5000	24.89	12.22	0.831571
5280	24.47	12.02	0.817961
6000	23.98	11.78	0.801629
6600	23.25	11.42	0.777131
7000	23.09	11.34	0.771687
7920	22.15	10.88	0.740384
8000	22.22	10.91	0.742426
10560	20.11	9.88	0.672334

$$1 \mu\text{L trace gas} * 0.965 \text{ atm} / ((0.08206 \text{ L atm Mol}^{-1} \text{ } ^\circ\text{K}^{-1}) * (273 + 20)^\circ\text{K}) * 1 \text{ L}/10^6 \mu\text{L} * 10^6 \mu\text{Mol}/\text{Mol}$$

When the value of $R = 0.08206 \text{ L atm Mol}^{-1} \text{ } ^\circ\text{K}^{-1}$ is used, units of P, V, n and T have corresponding units of Atm, Liters, Moles, and $^\circ\text{K}$, respectively. The goal of applying Eq. 2 is to convert $\mu\text{L trace gas}$ to $\mu\text{Mol trace gas}$. To do this, one must have

knowledge of both the air temperature and atmospheric pressure. A table relating elevation and atmospheric pressure is provided.

Sample calculation to convert $\mu\text{L gas}$ to μMol . (Note: conversion from $^\circ\text{C}$ to $^\circ\text{K}$ by adding 273)

calculated flux with units of $\mu\text{L trace gas m}^{-2} \text{ min}^{-1}$, by 0.0401 gives flux units of $\mu\text{Mol trace gas m}^{-2} \text{ min}^{-1}$. (Note above that $^\circ\text{K}=(273+ ^\circ\text{C})$).

Noisy Data

The change in chamber headspace trace gas concentration over time typically will be linear or curvilinear as shown in Figs. 3 and 4. In these situations linear regression or the non-linear diffusion based models can be used to calculate the flux. However, often concentration with time data are noisy and time course data are obtained similar to those shown in Figs. 5 and 6 (Anthony et al., 1995). Determination of a flux from noisy data often requires investigator judgment. Several possibilities exist for flux estimation from noisy data including: 1) linear regression using all the points, 2) calculation of the slope from points 1 and 2, 3) slope calculation from points 1 and 3, or 4) slope calculation from points 2 and 3. If the investigator cannot discount outliers based on experience and judgment of past performance of the site or chamber, the most conservative approach would be to adopt option 1. If noisy data proves to be a persistent problem, evaluation of GC precision, chamber design, and/or sampling protocols

should be performed. Also, collection of more points during chamber deployment may help in discriminating outliers and may also yield improved estimates if the Pedersen stochastic model is applied.

Minimum detection limit

Often field fluxes are low, thus it is important to have an idea of the minimum detection limit (MDL). The MDL is a function of the sampling and analytical precision as well as the chamber volume and surface area. Sampling + analytical precision is determined by calculating the standard deviation of many standards on the gas chromatograph ($n > 20$). Because instrument precision is usually a function of concentration, the standards used should contain trace gas concentrations at or near ambient levels. From analysis of large numbers of standards, precision is determined to be ± 2 standard deviations of the mean. This delta ppm ($2 \times \text{std dev}$), along with specific information on the chamber volume, surface area, and chamber deployment time is used to compute the MDL as described below.

MDL = $2 \times \text{std.dev uL/L} \times \text{Chamber Volume (L)} / \text{Chamber Footprint (m}^2) / \text{total deployment time (min)}$.

Units for the above computation of the MDL are $\text{uL trace gas m}^{-2} \text{ min}^{-1}$. To convert to $\text{uMol m}^{-2} \text{ min}^{-1}$ the universal gas law must be used.

Quality assurance /Quality control:

Standards and standardization:

It has been reported that Scott Standard Gases may differ substantially from their stated concentrations. An alternative source of certified standard gasses is Scott Marian (these are still only $\pm 2\%$ at best). If a network of ARS sites is going to be established, it is suggested two tanks of very high quality standards containing CO_2 , CH_4 and N_2O be purchased from NOAA at the cost of about \$3500 + new regulator (assuming that ARS will come up with some funds). These tanks should be shipped around for people to check their GC calibrations and their standard tanks. In the interim, Ft. Collins is arranging to have one of these standard tanks made, and there may be a possibility to distribute samples of this standard in vials to different locations on a limited basis. This known standard gas would then be used to standardize gas tanks at each location. Alternatively, it has been suggested that ARS fund a trace gas analysis lab where all samples are analyzed. At this point in time agency funds do not exist to support this proposal. Details of these activities will be worked out at a future date.

Stopper reactivity:

Currently, gray butyl rubber septa or stoppers appear to be the least reactive to N_2O and CH_4 ; however, there have been reports that different batches of gray butyl rubber may differ regarding their reactivity. It is recommended that individual investigators perform their own assessment of trace gas reactivity with each new batch of stoppers, regardless of the type of stoppers used. A suggested protocol for this is:

- 1: Prepare 60 vials with standard gas. This will be the test set.
2. Immediately after these vials are prepared, run 20 of these samples.
3. After one-day of storage (at room temperature and pressure), run 20 vials from the test set prepared on day 0, and prepare and run 20 newly prepared vials with the same standard used to prepare the test set.

4. After one-week of storage, run the final 20 vials from the test set along with 20 vials freshly prepared.
5. Evaluate: 1) Changes in average concentration as a function of storage. 2) Changes in precision (i.e. standard deviations) as a function of storage.

Syringe reactivity/carryover:

Plastic syringes will leak over time. If gases are stored at any length of time in syringes equipped with stopcocks, a similar test of storage efficacy should be performed with each new batch of syringes. Polypropylene syringes are not inert, however, cross-contamination due to carryover is usually not a problem unless high concentrations are sampled, and if syringes are flushed with air between use. Similarly, if syringes are reused, the investigator might want to perform an assessment of trace gas carryover.

Ancillary Measurements

In addition to the measurements prescribed by soil sampling protocol additional measurements are recommended.

At time flux is measured:

Air temperature

5 cm Soil Temperature

Soil Water content (0-6 cm) gravimetric, capacitance (Theta Probe), or TDR.

At time of chamber installation:

Bulk density, texture, organic C and N

Chamber headspace volume (average chamber height at several locations within the chamber multiplied by the chamber surface area)

Soil Nitrate and Ammonium (0-10 cm). **Note:** It is desirable that soil nitrate and ammonium be determined throughout the year at time intervals deemed appropriate by the individual investigator as dictated by resource availability and plot constraints.

Weather data - rainfall, air temperature, relative humidity, solar radiation.

Advice and Consultation

Several investigators involved in GRACEnet have experience in trace gas analysis and flux measurement. These people have agreed to serve as resource contacts for investigators with questions on GC set up, soils chambers, gas sampling, flux calculation, field variability, and data interpretation.

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Appendix D1: Example of Trace gas Flux Sampling Procedure

Set of 12 Anchors placed in pairs (in-row and inter-row) -

For each set of 12 Chambers:

1. Lay out Chambers, Vials, Syringes by each anchor
2. Install 5 cm temperature Probes (1 in each plot). Air temperature and chamber temperature probes in first plot only.
3. Take ambient Gas Sample
4. Start Measurement (t 0) - Start Stop Watch
 - a. Record Temperatures
 1. Place chamber on anchor #1 (vent facing downwind).
 2. Remove 10 ml gas sample.
 3. Inject sample into vial.
 4. Flush syringe with Air 2x.
 5. Place chamber on anchor #2.
 6. Remove 10 ml gas sample.
 7. Inject sample into vial.
 8. Flush syringe with air 2x.
 - b. Move to next pair of chambers in plot.
 1. Record time on stop watch.
 2. Place chamber 3 on anchor.
 3. Remove 10 ml gas sample.
 4. Inject into vial.
 5. Flush syringe with Air 2x.
 6. Place chamber 4 on anchor.
 7. Remove 10 ml gas sample.
 8. Inject into vial.
 9. Flush syringe with air 2x.
 - c. Move to next plot.
 1. Record Temperatures.
 2. Repeat steps 4b.1 through 4b.8 (above).
 - d. Repeat step 4c until all 12 chambers are in place and have been sampled for time 0.
5. First Time Point (t 1).
 - a. Move to position 1 (chamber 1).
 1. Record soil temperatures, record chamber temperature and air temperature.
 2. Insert syringe into chamber septa.
 3. When stopwatch shows t-1 time (e.g. 20 minutes), remove 10 ml Gas sample.
 4. Inject gas sample into appropriate vial.
 5. Flush syringe 2x.
 6. Move to next chamber, repeat steps 5a.2 - 5a.5, above.
 7. Continue until all chambers have been sampled for time 1
5. Second and third time points (t 2 and t-3).
 - a. same as step 5 above.
6. Remove all chambers, Move to next set of 12 anchors. Repeat steps 1-5.
7. When all plots have been done, one person collects all chambers and place in truck while other person takes soil moisture readings in each plot (4 measurements/plot).

Appendix D2: Suppliers

Sample Vials and Stoppers:

Option 1: Glass serum vials 6.0 ml (22 x 38 mm) and butyl rubber stoppers and aluminum crimps: Alltech, 2051 Waukegan Rd, Deerfield, IL 60015 (vial stock # 98768, butyl rubber stoppers stock # 95256). These vials fit in the custom autosampler described by Arnold et al. (2001).

Option 2. Exetainers, screw cap 12 ml vials that have a butyl rubber septa-same idea as the serum vials and butyl rubber stoppers-just cheaper and more or less disposable-can buy new screw caps and septa relatively cheaply. Exetainers are purchased through Labco Limited (Brow Works, Copyground Land, High Wycombe, Buckinghamshire. HP123HE, United Kingdom (phone 44-1494-459741) (fax: 44-1494-465101) (Email: sales@labco.co.uk or enquiries@labco.co.uk). The cost is about \$275/1000 vials. Our new CombiPal autosampler (purchased through Varian with a new GC and data system uses these vials. Exetainer vials recommended by Reynald Lemke at Swift Current. The Canadians have four of these instruments running-the autosampler has the capacity for 200 samples per batch.

Standard gases

Scott Speciality Gas <http://www.scottgas.com/>. Standards come certified at +/- 5%; however, actual concentrations may be suspect.

Scott Marian.

Syringes: Beckton-Dickenson (obtained from most laboratory supply companies)

Syringe stopcocks: (ColeParmer # A-30600-000: Qosina, #99705 or #99717).

Reflective Tape:

Industrial Tape Connection: <http://www.tapeconnection.com/>

Silver 0.9 mil Metalized Mylar Polyester Film with a brilliant, vibrant mirror-like finish; coated with an aggressive long lasting acrylic adhesive system. 2"x72yards Mylar Film Tape
Alternative to 3M #850; Ideal #505; Tesa #4137; TLC #CT941M; Venture #1555CW
PRICE: \$32.70/roll

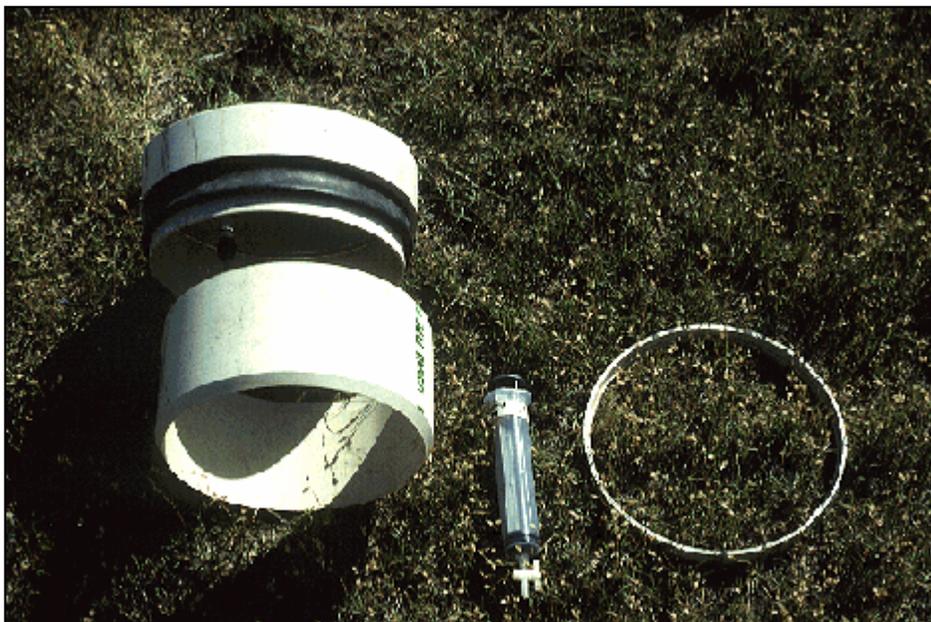
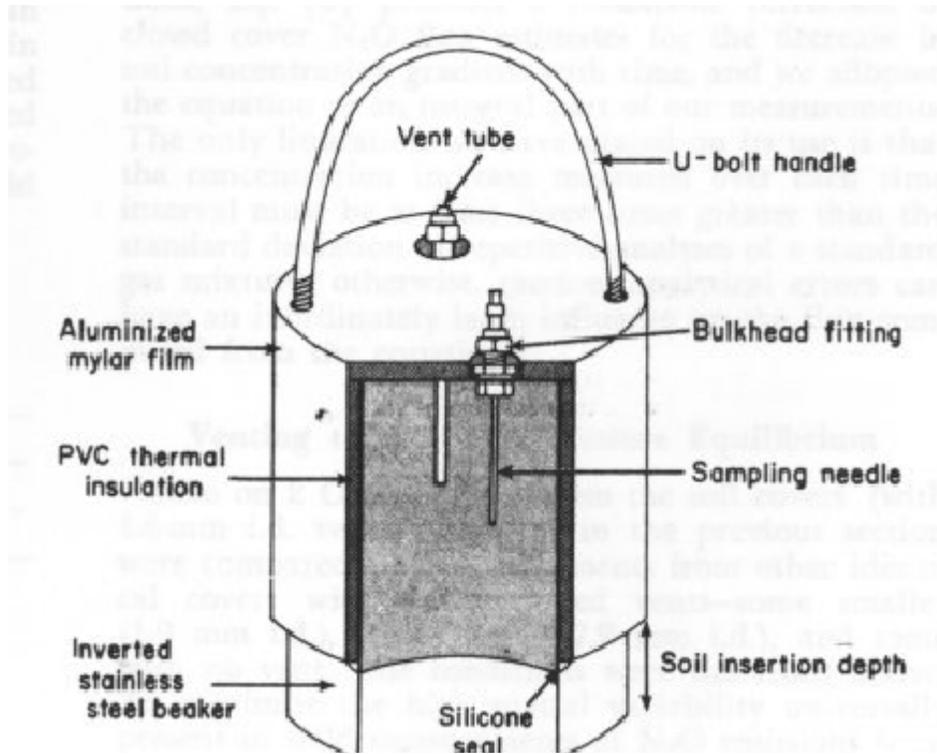
Gas Manifolds:

Small Parts, Inc. 800-220-4242, www.smallparts.com. An example part no. is TCM-13-20/4-10 (description = Tubing Manifold 13G inlet 20G outlet).

Recirculating fans:

Computer fans can be obtained from Action Electronics, Santa Anna, CA. Phone: (800) 563-9405, www.action-electronics.com. Example of a 12vdc fan from this company is part # 108idc12vdc1b. This fan is 25 mm x 25 mm x 10 mm and can be run on a 9 volt transistor radio battery.

Appendix D3. Sample chamber designs, photos and schematics.



PVC soil anchor and chamber used by Mosier.



Rectangular chambers used by Mosier



Example of temporary/portable chamber used by Parkin. Chamber has an attached polylethylene skirt held in place on the soil surface with a length of chain. As shown, the chamber is monitoring soil CO₂ flux by recirculating gas through an infrared analyzer. Gas samples can be withdrawn through septum in top of chamber for N₂ and CH₄ analyses.

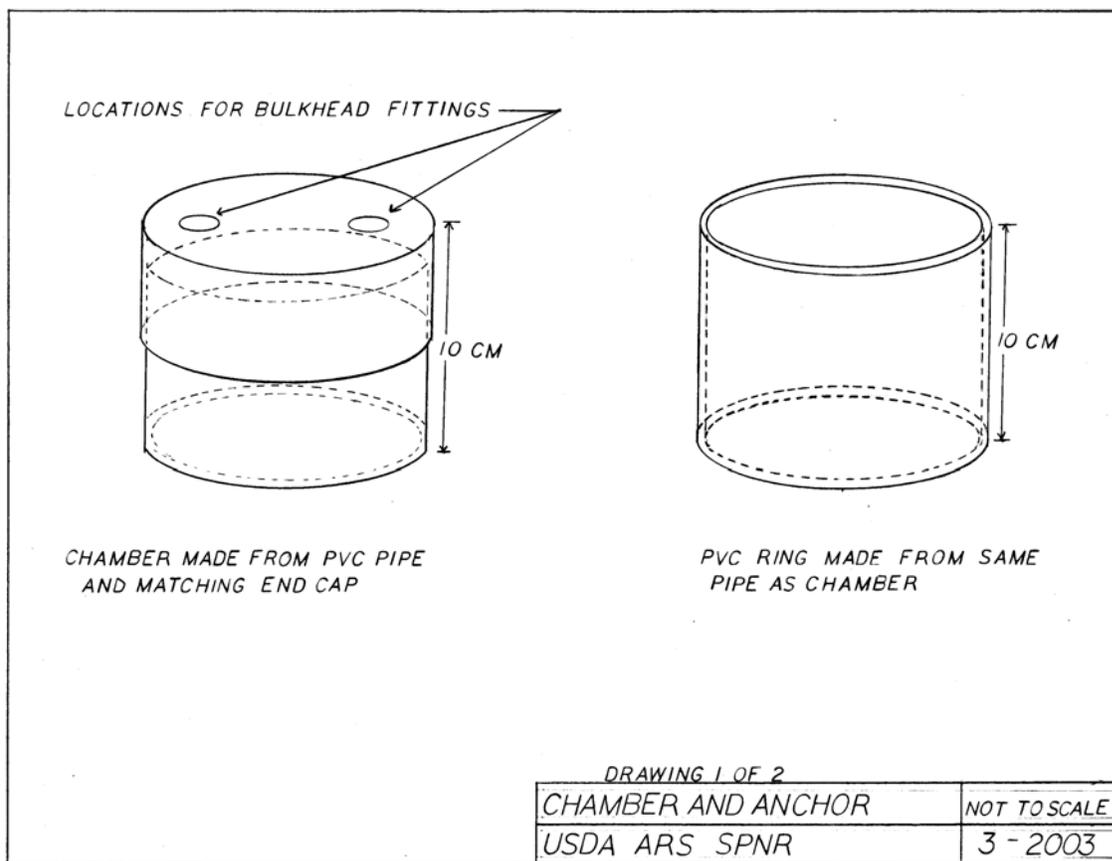


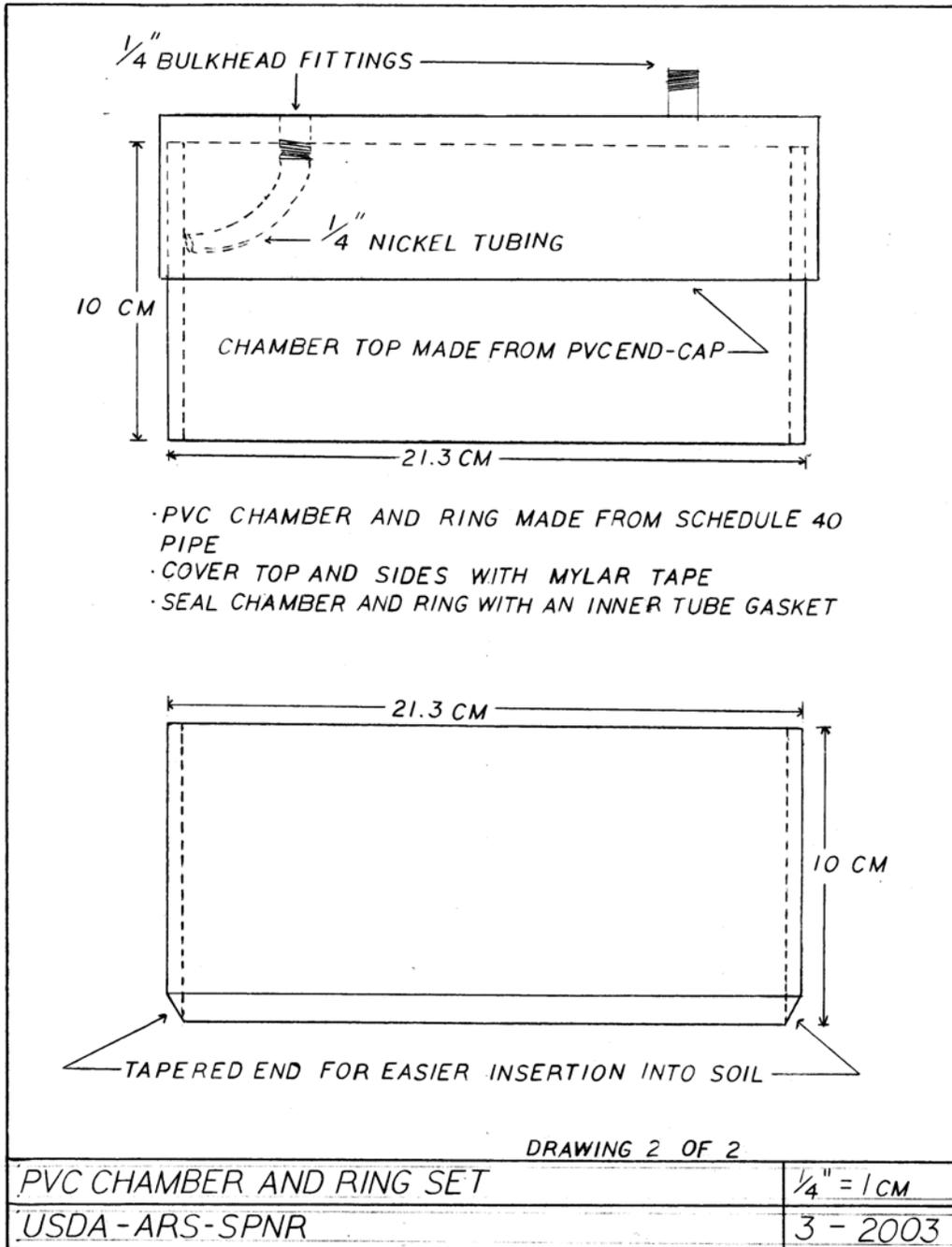
Large skirted chamber used for CO₂ flux from corn/soil system.
Applicability of chamber for N₂O and CH₄ flux measurements has not been tested.

Round PVC chamber description:

Anchor: Made from PVC pipe, 15 – 30 cm diameter. It can be tapered on the bottom for easier insertion into the soil. We typically insert the anchor 8-9 cm into the soil. The chamber can fit onto the anchor, flush (resting on the anchor), inserted into the anchor, or if an end cap is used, fit over the anchor. A seal is made using an approximately 5 cm wide tire inner tube.

Chamber: The chamber can be made from a PVC pipe end cap of the appropriate size or a piece of PVC pipe with a top made from sheet PVC or plexiglass that is cut to fit and cemented into place. Two holes, to accommodate swagelock fittings are drilled and tapped in each chamber top.

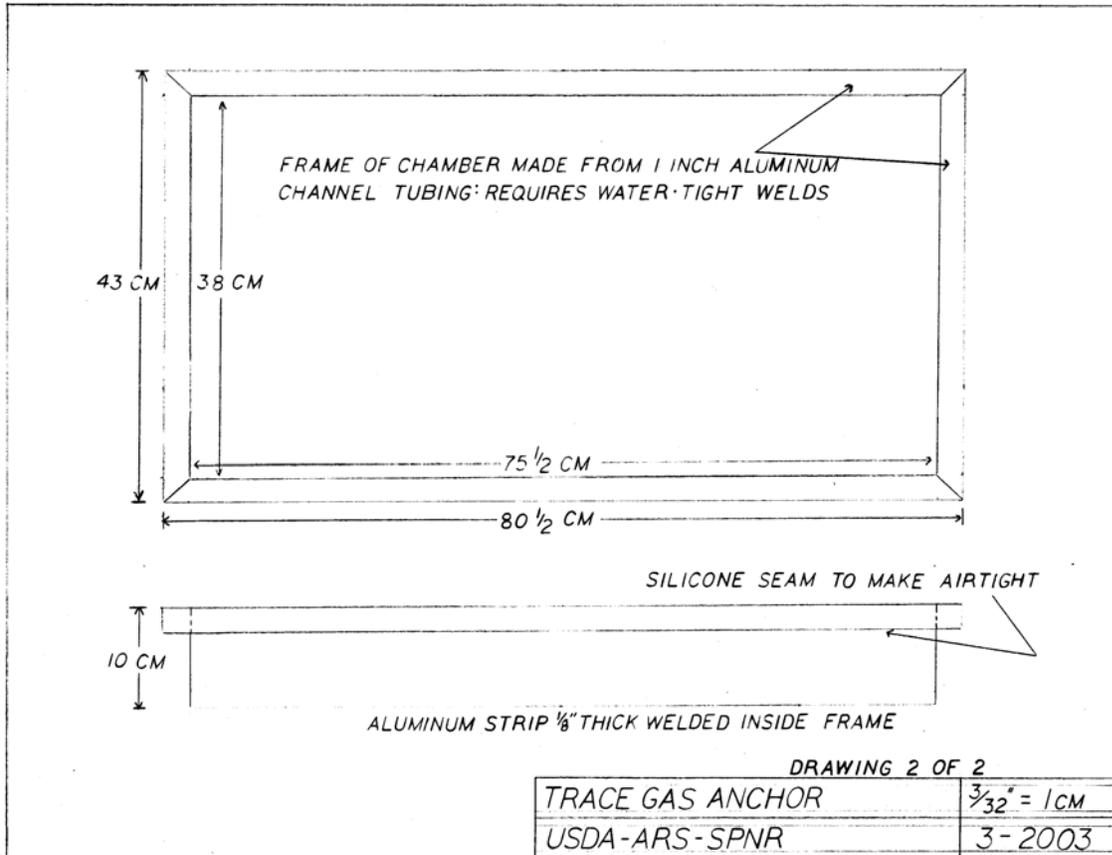


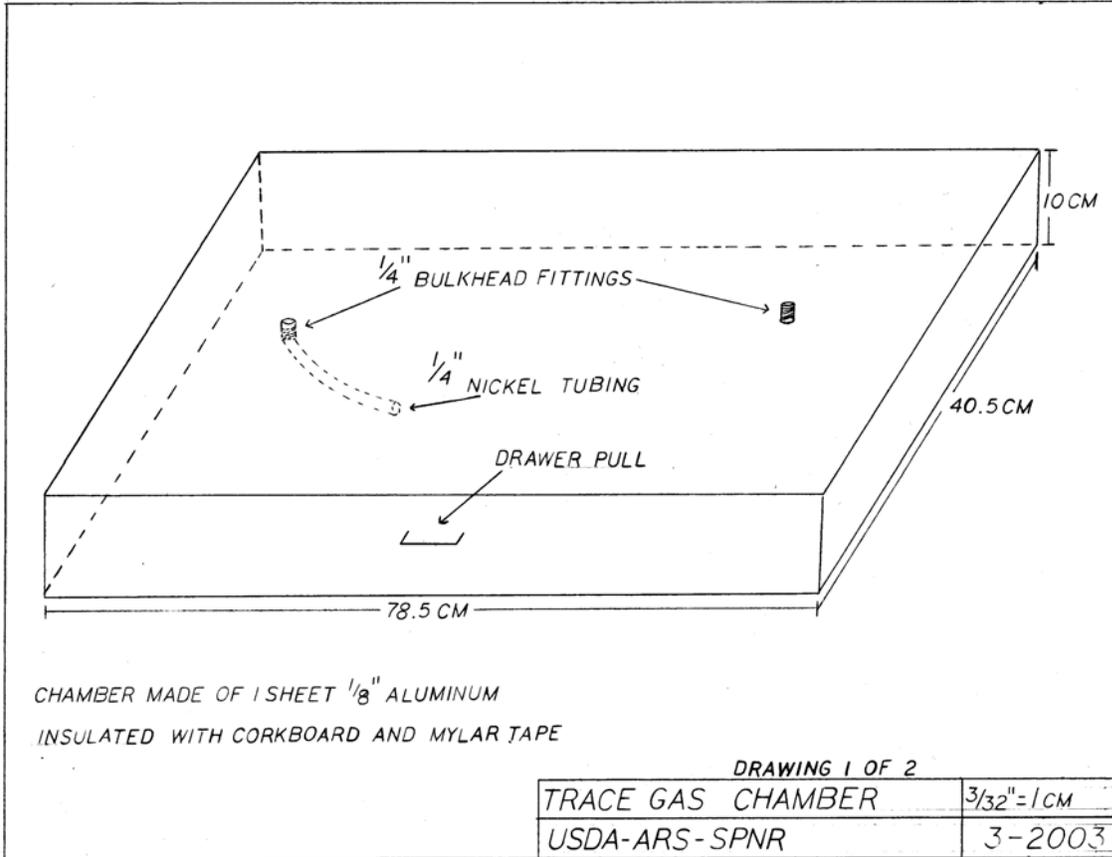


Rectangular aluminum Chambers: Made from sheet aluminum. These can be made any size to fit the field situation.

Anchors: Made from sheet aluminum with a trough to hold water that has been welded on top. The anchors are inserted 10 cm into the soil.

Chamber: Made from sheet aluminum to desired dimensions. Two holes, to accommodate swegelock fittings for vent tube and gas collection septum are drilled and tapped in each chamber top.





Appendix E. Micrometeorological measurements

Steering committee: John Baker, Bruce Kimball (*Who else in on this committee?*)

Weather and climate data sets for all GRACENET locations will be necessary, both for interpreting other measured field data and for the added value obtained through modeling of C processes. It is important to distinguish between weather and climate data. Climatic data are needed for general site characterization and for generating long-term simulated weather variables for modeling. In general, proximity is not as critical as the quality of the data and the length of the record. The nearest weather station for which data are archived at the National Climatic Data Center should be sufficient. Standardized methodology (e.g., Easterling et al, 1996) should be used to extract and develop climatic data that are used for GRACE.net purposes.

Current weather data, needed in conjunction with specific field experiments, must be measured as proximally as possible. Ideally, all research locations will have weather stations on site, or at least sufficiently close that the data will be sufficiently representative. This criterion is inexact, and varies for different weather variables; as a general guideline it is desirable to have a basic agricultural weather station (Hubbard and Hollinger, 2005) within 2 km of each field research site. In this context precipitation is the most critical parameter. If the nearest weather station is more than 1-2 km distant, it is recommended that a rain gauge be installed on site.

The suggested minimum data set for weather should include the following:

Daily weather

- Air temperature maximum (°C)
- Air temperature minimum (°C)
- Average dew point (°C)
- Daily total precipitation (mm)
- Daily total solar radiation (MJ/m²)
- Average daily wind speed (m/s)
- Average daily 10-cm soil temperature (°C)

Optional data, that are desirable for many purposes but not deemed absolutely necessary, include the following:

- Wind direction (degrees from north)
- Pan evaporation (mm)
- N deposition, wet and dry
- Net radiation (MJ/m²)
- Rainfall intensity (mm/hr)
- Soil heat flux (MJ/m²)
- Soil temperature profile ((°C)
- Soil water content profile (m³/m³)
- Snow depth (mm)

In addition, for detailed mechanistic modeling it may be necessary for some sites to collect weather data with higher temporal resolution, e.g.-30 minute or hourly. These sets would typically include:

- Air temperature

- Relative humidity (%) or dew point (°C)
- Wind speed (m/s)
- Solar radiation (W/m^2)
- Net radiation (W/m^2)
- Precipitation (mm)
- Canopy temperature (°C)
- PAR, incoming ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
- PAR, reflected ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
- Soil heat flux (W/m^2)

Details regarding the proper measurement of all variables can be found in Hatfield and Baker (2005). Measurement heights and instrument type should be reported for all measurements.

Climate data

Climate data are expected to include the following:

- Mean monthly air temperatures (°C)
- Annual mean maximum and minimum air temperature (°C)
- Total monthly and annual precipitation (mm)
- Annual snowfall (mm)

Literature cited:

- Easterling, D.R., T.C. Peterson, and T.R. Karl. 1996. On the development and use of homogenized climate datasets. *J. Climate* 9(6):1429-1434.
- Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy Monograph no. 47. American Society of Agronomy, Madison, WI. 584 pp.
- Hubbard, K.G., and S.E. Hollinger. 2005. Standard meteorological measurements. *In* Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy Monograph no. 47. American Society of Agronomy, Madison, WI. 584 pp.