Journal of Environmental Quality SHORT COMMUNICATIONS

Introducing the GRACEnet/REAP Data Contribution, Discovery, and Retrieval System

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Difficulties in accessing high-quality data on trace gas fluxes and performance of bioenergy/bioproduct feedstocks limit the ability of researchers and others to address environmental impacts of agriculture and the potential to produce feedstocks. To address those needs, the GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement network) and REAP (Renewable Energy Assessment Project) research programs were initiated by the USDA Agricultural Research Service (ARS). A major product of these programs is the creation of a database with greenhouse gas fluxes, soil carbon stocks, biomass yield, nutrient, and energy characteristics, and input data for modeling cropped and grazed systems. The data include site descriptors (e.g., weather, soil class, spatial attributes), experimental design (e.g., factors manipulated, measurements performed, plot layouts), management information (e.g., planting and harvesting schedules, fertilizer types and amounts, biomass harvested, grazing intensity), and measurements (e.g., soil C and N stocks, plant biomass amount and chemical composition). To promote standardization of data and ensure that experiments were fully described, sampling protocols and a spreadsheet-based data-entry template were developed. Data were first uploaded to a temporary database for checking and then were uploaded to the central database. A Web-accessible application allows for registered users to query and download data including measurement protocols. Separate portals have been provided for each project (GRACEnet and REAP) at nrrc.ars.usda.gov/slgracenet/#/Home and nrrc.ars.usda.gov/slreap/#/Home. The database architecture and data entry template have proven flexible and robust for describing a wide range of field experiments and thus appear suitable for other natural resource research projects.

J. Environ. Qual. 42:1274–1280 (2013)
doi:10.2134/jeq2013.03.0097
Freely available online through the author-supported open-access option.
Received 18 Mar. 2013.
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Both research and policy-making needs are increasing the demand for comprehensive, thematic databases with information describing agro-ecosystem performance (Morgan et al., 2010). Technical journals and scientific societies are also increasing their efforts to encourage authors to make their data more available for others (e.g., http://esapubs.org/esapubs/emonTypes.htm#Dat). Increased data availability, with descriptions of measurement protocols, can facilitate meta-analyses, model building and testing, and provide transparency of methodologies used to generate data. Having access to high-quality, vetted data can improve understanding of the key biogeochemical processes affecting agricultural production and the environment. Increased data availability is likely to facilitate identification and adoption of best management practices, thus helping to mitigate undesirable impacts of agriculture on air, soil, and water quality, while maintaining or increasing production of food, feed, fiber, and fuel.

Databases are essential for managing data in a digital format, but creation of a database alone does not solve issues of standardized data collection protocols, data entry, quality control, user access, and monitoring use. Data entry can be facilitated through standardized data entry templates (and associated software). Data quality can be assessed in intermediate steps before final loading into a central database.

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Abbreviations: GHG, greenhouse gas; GIS, geographic information system; GRACEnet, Greenhouse gas Reduction through Agricultural Carbon Enhancement network; REAP, Renewable Energy Assessment Project; SQL, structured query language.

Once data are incorporated into a database, long-term storage and oversight capabilities must exist to manage, update, and retrieve the information. A complete data management system helps users to perform analyses that increase our understanding of how environmental and land management factors interact to influence plant growth, soil quality, trace gas exchange, and numerous other agro-ecosystem services that may be of concern.

GRACEnet and REAP are USDA–ARS nationwide projects. The primary goals of GRACEnet are to quantify greenhouse gas (GHG) emissions and other environmental impacts of cropped and grazed systems under "business as usual" management and to assess how those impacts change with management scenarios intended to increase soil carbon stocks and reduce GHG emissions (Jawson et al., 2005). The major goals of REAP are to determine sustainable rates of biomass feedstock harvest and to identify other management practices that safeguard soil resources while ensuring that increasing demands for food, feed, fiber, and fuel can be met (Johnson et al., 2006). Both projects involve conducting large numbers of field experiments that utilize standardized data collection protocols (Karlen, 2010; Follett, 2010) to document how environment and management impact crop yields and the natural resource base.

While developing a data management system for GRACEnet, we found that by planning for a few additional types of measurements, the data management system could readily be adapted for many other types of projects. This adaptability was demonstrated by incorporating data from REAP with minimal additional costs to the scientific contributors, data analysts, system developers, and system administration. Our objectives here are to provide an overview of the GRACEnet and REAP data management system to inform readers and to encourage innovations in such a system. Features described in this communication include the data entry tool, temporary databases for data checking, architecture of the main database, types of data included, and accessing the Web interface.

Overview of GRACEnet and REAP Projects

The USDA–ARS scientists affiliated with the GRACEnet and REAP projects are currently located at 19 and 14 locations, respectively, across the United States (Fig. 1), with several of the locations contributing to both projects. GRACEnet contributors conduct field experiments that measure soil C and/or GHG emission data for "business as usual" management (Scenario 1) and at least one of three additional scenarios: an agricultural system that most likely maximizes soil C sequestration, a system that minimizes net GHG flux, or a system that maximizes net environmental benefits (Jawson et al., 2005). Anticipated outputs from the GRACEnet project are (i) data for a national assessment of GHG flux, C storage, and model driver data, (ii) regional and national guidelines for how management practices influence soil C and GHG emissions, (iii) development and evaluation of computer models designed to estimate regional- and larger-scale GHG emissions for national inventories (e.g., USEPA 2013) and to investigate the impacts of different management practices on crop yields, GHG emissions, and NO_3 leaching (e.g., Davis et al., 2012) and (iv) summary papers (ars.usda.gov/research/programs/programs.htm?np_code=212&docid=21223) for use by action agencies and policymakers (Liebig et al., 2012).

The objectives of REAP were (i) to determine the amount of crop residue needed to protect the soil resource, (ii) to compare short- and long-term tradeoffs for use of crop biomass as a bioenergy feedstock versus a soil carbon source, and (iii) to provide recommendations and guidelines for sustainable biomass harvest to the U.S. Department of Energy, producers, and other cooperators (Karlen et al., 2008). Project outputs include (i) guidelines for management practices supporting sustainable harvest of residue, (ii) algorithm(s) to estimate the amount of crop residue that can be sustainably harvested, and (iii) decision support tools and guidelines that describe the ecological and economic trade-offs between residue harvest and retention for soil protection and C sequestration (http://www.ars.usda.gov/research/programs/programs.htm?np_code=202&docid=15193).

Data Management Requirements

After it was determined that the most efficient way to meet the broad GRACEnet and REAP project goals was to incorporate data from all research locations into a Web-accessible database, iterative discussions among field researchers, model developers, software and database staff, and research support staff were held to establish data management system requirements. Consensus was reached that in addition to measurement data, the system must have sufficient data to fully describe a field experiment. This provides clear documentation of experimental methodology, including management practices and natural resource and environmental conditions, thus facilitating independent analysis of results and additional hypothesis testing. This also provides inputs needed by modelers for simulating performance of crop or grazing land agro-ecosystems. This decision established the requirement for documenting management practices, initial soil conditions, daily weather, and other information ultimately required as model inputs. A second decision was that the database should accommodate multiple experimental designs, not overly constrain the number and types of factors considered, and permit researchers to enter data at both individual plot and treatment mean levels. For example, a field experiment investigating the effect of fertilizer addition on crop yields could have four plots that were chosen randomly within the field that all received the same amount of fertilizer and were subjected to identical management practices. Yields could be reported for each of the four plots separately, or a single average (mean) yield for the four plots could be reported (treatment mean). In the latter case, the standard deviation of yields would also be reported. Comparisons among GRACEnet experiments indicated the need to document potentially important differences for within-plot sampling such as whether gas flux chambers were located within or between crop rows. The third critical decision was that rather than assuming practices at individual locations could be described using standardized metadata, the database would allow researchers to describe their specific field measurements and protocols in designated tables, thus facilitating the storage and sharing of all available data.

The defined scope for the data management system was sufficiently large and complex that we realized a standard data entry protocol was required. It was also agreed that data entry should be relatively simple to minimize technical support required for this activity. This led to development of a spreadsheet-based data-entry template that also served as a flexible tool for testing prototypes of the database architecture. Although both GRACEnet and REAP projects encourage measurement of common variables using standardized methodologies at all locations, it was recognized that this is not entirely possible because of variability among cropping (or grazing) practices, experimental design, and other factors. Consequently, the data-entry template was designed to accommodate diverse types of data reported at various spatial and temporal scales. It is also important to recognize that it is neither expected nor essential for any single experimental site to provide all of the various types of data that the template can accommodate. This flexible data-entry protocol also simplifies the addition of new types of measured or metadata needed to address future research objectives.

Design of the database system was influenced by other data management systems (Hunt et al., 2001; Ojima et al., 2000; Steiner et al., 2003) and consideration of requirements for specific agro-ecosystem models such as DayCent (Del Grosso et al., 2012) and CQESTR (Gollany et al., 2012). Design of the database started with development of the spreadsheet-based data-entry template in 2006. The template was reviewed and refined by GRACEnet and REAP scientists and by USDA–ARS information technology personnel during subsequent years. During 2009 and 2010, a data dictionary, database protocol, and data access policies were established. In 2011, a data management team was formed consisting of USDA–ARS scientists, information technology personnel, and technicians, and a relational database was tested with data from five GRACEnet experiments. In 2012, a data curation team was formed and technicians were designated as points of contact to serve as liaisons and help researchers populate the data-entry template. Also in 2012, the GRACEnet and REAP data-entry templates were unified as a single tool, and the query and download applications of the central database were improved. In February 2013, a BETA version of the GRACEnet/REAP database system was made available to the public, with future updates to be made in fall 2013. Subsequent versions will be released biannually.

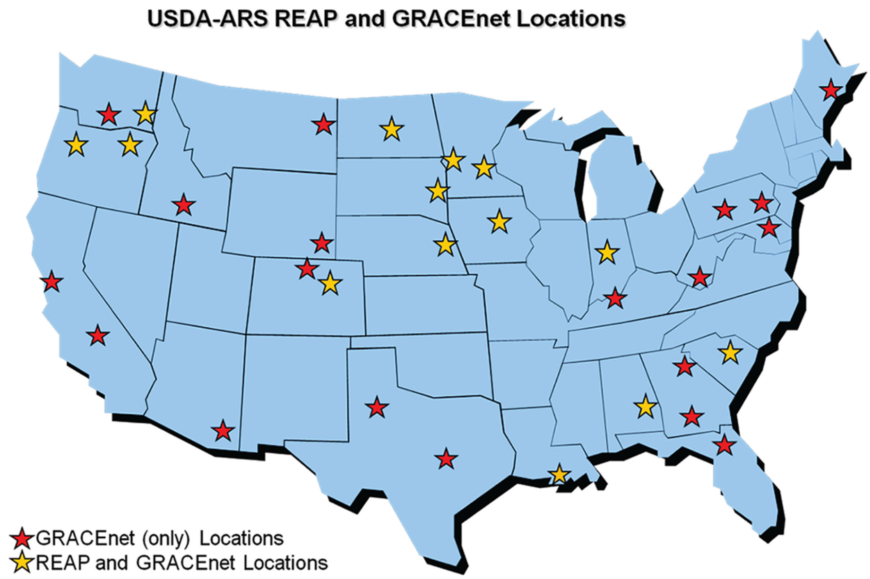

Fig. 1. Map of GRACEnet and REAP locations in the United States.

Database Description

Three components comprise the data management system (Fig. 2): the spreadsheet-based data-entry template, temporary databases used for quality control (implemented in Microsoft Access), and the central relational database (implemented in Microsoft SQL Server 2008). The data-entry template includes tabs with instructions, research location and experimental site information, agricultural system management information, and measurement data (Table 1). Worksheets within the template contain fields in which qualitative and/or quantitative data can be entered. Fields contain user instructions, drop-down lists for qualitative data, and numerical units for quantitative data.

Two data fields are required to relate data across tabs in the spreadsheet: treatments and experimental units. Treatments describe what was experimentally manipulated (e.g., crop rotation, fertilizer amount, tillage intensity, biomass removed). Experimental units convey information regarding the spatial layout of plots, nesting of treatments, plots and replications, and the spatial granularity at which treatments are imposed and measurements conducted. The experimental unit concept is crucial because different treatments are implemented and measurements are taken on specific experimental units, but they are not necessarily at the same spatial scales. For example, an entire field could have the same treatment in terms of crop rotation, but plots within the field could have different tillage intensities, and subplots could have different amounts of synthetic fertilizer applied. Measurement data can also be reported at different spatial resolutions (e.g., crop yields can be reported at the plot level while soil carbon might be reported

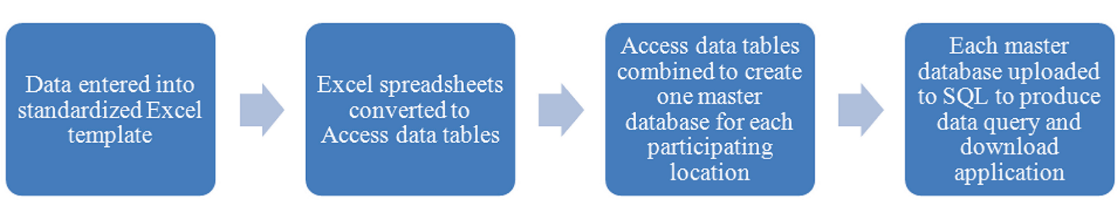

Fig. 2. Diagram of GRACEnet/REAP data conversion process.

at the replicate, or subplot, level). Users have flexibility to designate plot and treatment hierarchies that properly represent their experimental treatments and the scales at which different measurements are made. The template is designed to accommodate nested experimental units up to five layers deep (e.g., replications, within subplots, within plots, within fields, within a site). Because all measurement and management data are reported at the treatment and experimental unit level, it is essential that contributors clearly delineate all relevant components of the experimental design and plot layout.

Completed data entry templates from GRACEnet and REAP locations are sent to data liaisons to convert into the Microsoft Access database using automated software (Fig. 2). Location refers to a group of USDA–ARS scientists working to investigate a common research theme such as agricultural impacts on soil processes. Location-specific Microsoft Access databases are then combined into a single Microsoft Access database. This Microsoft Access database is then uploaded to a server containing Microsoft SQL Server and imported into a SQL Server database. Structured query language (SQL) scripts are performed on the SQL Server database to create additional information needed for the Web application.

Data Reporting, Quality Control, and Resource Requirements

Data contributors are responsible for entering their data in the data-entry template. During data entry, values are checked against expected minimum and maximum values, formats are standardized (e.g., for calendar dates), and treatment designations and experimental units are verified across data sheets. Additional quality control is conducted on conversion to Microsoft Access, and contributors are encouraged to download their data from the SQL system and perform a final quality check. Both GRACEnet and REAP assume that researchers require time to analyze data, perform quality control, review data entry internally, and publish their findings before uploading to the database. Researchers are expected to contribute data after publication, and the system is currently updated with newly contributed data on a semiannual basis. This does not imply that all researchers must contribute data semiannually, only that the system will be updated to include any new data that may have been uploaded. This allows

Table 1. Overview of tables housed in the GRACEnet and REAP applications.

Page names	Information found on page	Information type
Instructions	Directions regarding how to populate the template	Instruction
TablesOverview	Description of tables included in template	Instruction
ProjectOverview	Description of research project(s) for gathering data	Metadata
Locations	About your site	Metadata
Persons	Persons involved in a given experiment	Metadata
Citations	Publications about this research	Metadata
Treatments	Research treatments	Metadata
ExperUnits	Experimental units or plot identification	Metadata
MapPhotos	Map and photos of experimental layout	Metadata
Methods	Methods used	Metadata
WeatherStation	Location of your weather station	Characterization
WeatherDaily	Weather data from your site	Characterization
MgtAmendments	Amendments that were added, e.g., fertilizer, pesticides, etc.	Management
MgtPlanting	How you planted	Management
MgtTillage	How you tilled	Management
MgtGrowthStages	The stage of plant development at time of observation	Management
MgtResidue	How residue was removed during the experiment	Management
MgtGrazing	Grazing information	Management
MeasSoilPhys	Physical soil measurements	Measurement
MeasSoilChem	Chemical soil measurements	Measurement
MeasSoilBiol	Biological soil measurements	Measurement
MeasSoilCover	Percentage of soil covered with plant residue	Measurement
MeasGHGFlux	Greenhouse gas flux—nitrous oxide, carbon dioxide, and methane emission or consumption	Measurement
MeasHarvestRemoval	What was harvested and what remained in the field	Measurement
MeasPlantFraction	Mass, C, and N of harvested plant fractions	Measurement
MeasBiomassCHO	Biomass carbohydrates	Measurement
MeasBiomassEnergy	Energy from biomass, calorific value	Measurement
MeasBiomassMinAn	Mineral analysis of the biomass	Measurement
MeasGrazingPlants	Grazing plants biomass	Measurement
MeasSuppRes	Supporting research—items you cannot find a place for but think others would want to see	Measurement
AllCellComments	Comments people looking at your data might want to read	Comments
DropDownLists	Lists for names that allow you to use drop downs	Bookkeeping
ValueDomains	A listing of all the variables on all the pages	Bookkeeping
ValidationData	Quality assurance page; used by macros to check high and low values	Bookkeeping

data to be uploaded and reviewed internally before it is posted to the public database. Contributors are expected to follow standardized measurement protocols (Follett, 2010; Karlen, 2010), report deviations from these protocols, design statistically valid experiments, and conduct measurements at sufficient spatial and temporal resolution to ensure that valid inferences can be drawn. For example, it would not be acceptable to sample soil trace gas fluxes only 5 to 10 times per year because emissions have high temporal variability. In contrast, it is valid to measure soil organic C stocks only once per year, but as with trace gas fluxes, there should be a sufficient number of sampling repetitions to account for spatial variability. Publication of site-level results in peer-reviewed journal articles provides evidence that proper protocols regarding experimental design, measurement methods, and sampling intensity were followed.

Hardware, software, and personnel resources are required to establish and maintain the system. A distributed server approach (Bruck et al., 2004) is used to allow for key components to continue running in the case of failure, and an outfacing server that uses reverse proxy technology helps ensure security (Araujo et al., 2005). This involves using a public-facing server to pass GRACEnet/REAP application requests to distinct backend servers where the requests are executed (Fig. 3). Responses to requests are then returned to the public-facing server. Core and failover applications are housed on two distinct servers. This ensures that the application is always available because a district backup application address is utilized. The backup address is accessible on a different set of servers, so if the main servers are down, the backup address can be accessed. Map services that are used by the Web application to display geographical information are housed on a separate server that runs ESRI SDE (ESRI, Inc., Redlands, CA). The basic configuration is similar to that used for the Sustaining the Earth's Watersheds, Agricultural Research Data System (STEWARDS) described by Steiner et al. (2009). A data curator only needs to interact with SQL server and Map Server to manage and maintain data in the system. The software developer interacts with the development server, where all code revisions and additions are made. The developer then publishes the application to the application server, which is accessed by the public-facing server. The developer uploads data to a database server that the application uses as well. Finally, the developer uploads maps to a geographic information system (GIS) server where map services are created and are used by the application (currently, geospatial capabilities are limited to experimental site visualization). Thus, five different servers are used for the GRACEnet/REAP application.

Access to the Database

Instructions regarding how to register to use the data management system are available to new users at the GRACEnet (nrrc.ars.usda.gov/slgracenet/#/Home) and REAP (nrrc.ars.usda.gov/slreap/#/Home) sites. Once registered and logged on, users are offered a choice of tabs to explore data classified by types of data available, locations contributing data, crops grown, management practices, soil amendments, and grazing intensity (Fig. 4). Users can query and view data on screen or download

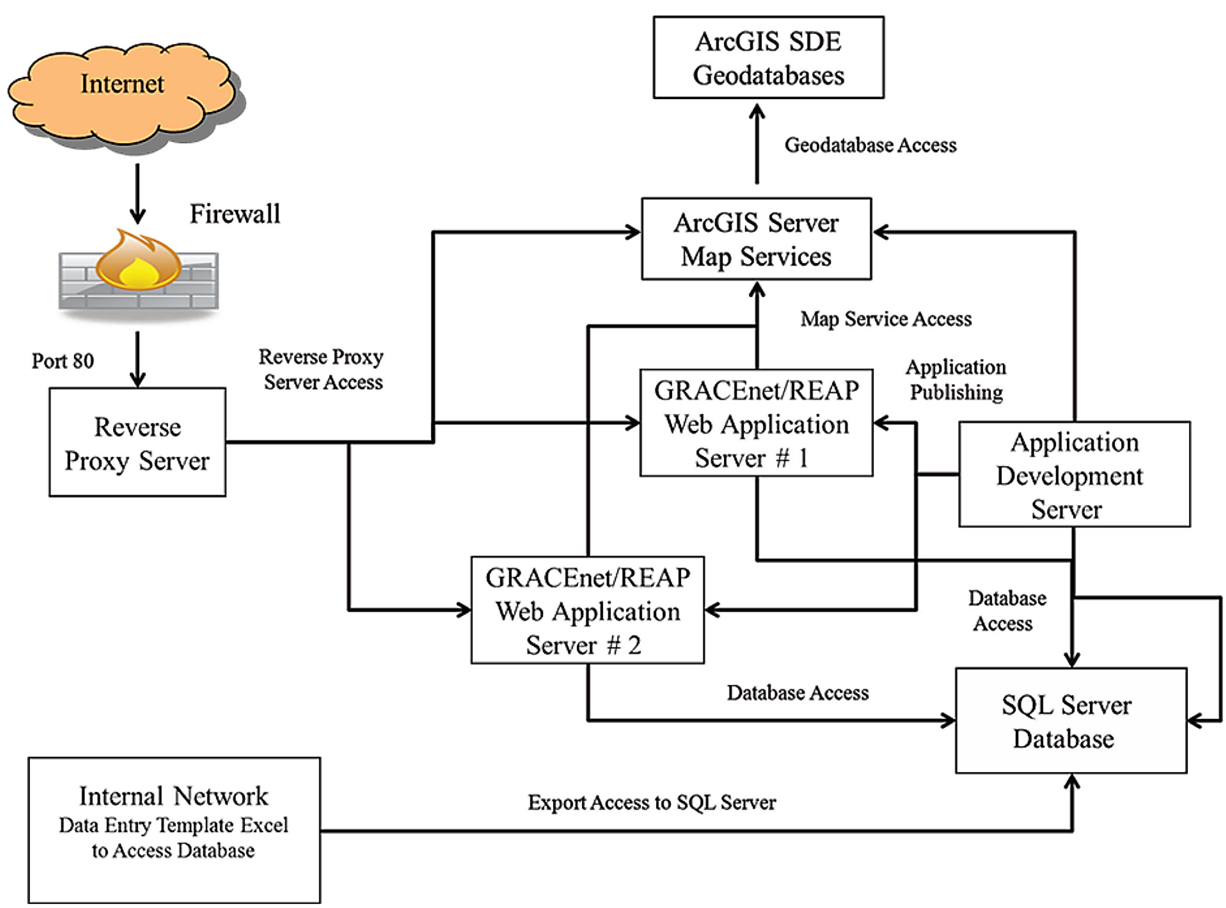

Fig. 3. Diagram of GRACEnet/REAP data system configuration.

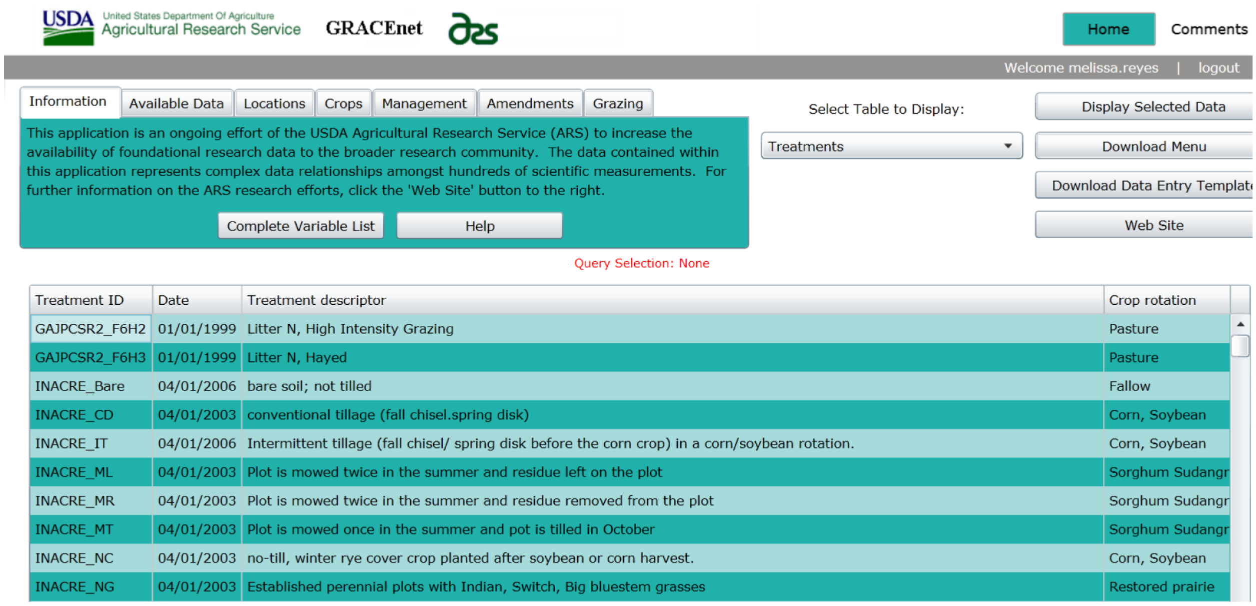

Fig. 4. GRACEnet query interface showing tabs for Locations, Crops, Management, etc. from the GRACEnet/REAP data discovery tool available at nrrc.ars.usda.gov/slgracenet/#/Home and nrrc.ars.usda.gov/slreap/#/Home.

XML files with desired data fields (Fig. 5). For example, users can choose to download all records for a particular location, or a subset of records from multiple locations that have common management practices (e.g., wheat/fallow rotations) or common measurements (e.g., CH_4 flux). Note that some fields (e.g., location, citations, treatments, experimental units) are included with all queries and downloads.

Current Database Contents

The GRACEnet and REAP initiatives have prompted 33 USDA–ARS units nationwide to contribute data thus far. For the GRACEnet project, this equates to 169,858 individual measurements from 25 different field sites, 40,793 management records, and 51,816 descriptors of background information encompassing location information, weather data, associated publications, and plot designations. The contributions of data are either associated with or in addition to over 400 refereed journal articles, books, book chapters, and proceedings. Currently, measurement data includes extensive soils information, GHG flux data, biomass production and grain yield, and microbial analyses. Management records refer primarily to field operations (e.g., planting and fertilization rate, tillage, etc.) but can also include plant growth stage and residue removal rates. The REAP entries currently consist of 33,049 individual measurements from 15 different sites, 11,864 management records, and 25,148 background records. Experiments represented in the database range from 1983 to 2012 for GRACEnet and from 1998 to 2012 for REAP.

Broader Context and Future Plans

By using a shared data-entry template and query interface to collect and disseminate data, research projects such as GRACEnet and REAP promote data sharing at national and international levels. Such large-scale enterprises have potential to allow researchers to better quantify and ultimately assuage GHG emissions, sequester atmospheric CO_2, and encourage best-management practices to improve air, soil, and water quality, and decrease reliance on fossil fuels. The relative simplicity of data entry and development of simple data screening tools by the technical support personnel have substantially increased willingness of other scientists to contribute information to the

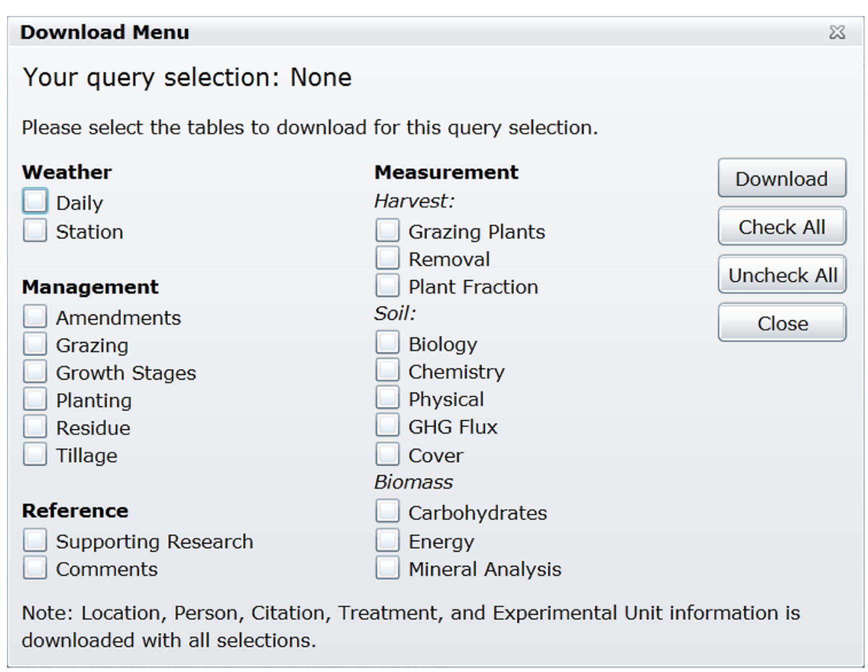

Fig. 5. Menu options for data downloads from the GRACEnet/REAP data discovery tool available at nrrc.ars.usda.gov/slgracenet/#/Home and nrrc.ars.usda.gov/slreap/#/Home.

database. Success of these projects creates more opportunities to enhance and expand the impact of the research being performed. Data content could be expanded temporally, spatially, and thematically. Presentation of data can be improved by including GIS spatial technologies and by including a time component. For example, color-coded graphics could show how N_2O emissions change over time for a particular plot, or users could query plots and highlight those where emissions exceed a designated value. Already, the project has expanded collaborative opportunities across organizational and professional boundaries.

Opportunities exist to expand the application of technologies to new research efforts. Many other research initiatives need similar database systems to support their work, and there will be many unknown opportunities to be discovered by users of the database system. Currently, collaborations with other U.S. projects interested in data management systems (e.g., the National Agricultural Library, Long Term Agricultural Research Network, Conservation Effects Assessment Project, and NIFA CENUSA) are in place to improve sharing and search capabilities. Member nations of the Global Research Alliance (Shafer et al., 2011) have also shown interest in using similar sampling protocols and recently developed data management systems. The data-entry template is freely available (http://www.ars.usda.gov/research/programs/programs.htm?np_code=212&docid=21223), and protocols will be developed in the future for non-ARS scientists who want to contribute data to the system. Accomplishing project goals and fully exploiting data sharing requires sufficient hardware, software, and personnel resources. Financial and leadership commitments from the USDA–ARS, other agencies and institutions, and interested stakeholders will undoubtedly help ensure that data generated by USDA–ARS scientists and their collaborators within other institutions and agencies will be used to their fullest potential to serve societal needs.

Acknowledgments

The authors thank the GRACEnet and REAP data contributors for their individual research efforts, USDA–ARS National Program Staff, and members of the data management and curation teams. Funding for this project is provided by the USDA-ARS, as part of the USDA–ARS GRACEnet and USDA–ARS REAP projects. Additional funding was provided from the North Central Regional SunGrant Center at South Dakota State University through a grant provided by the USDOE Office of Biomass Programs under award number DE-FC36-05GO85041.

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