Action Plan:

Introduction

Background

'Global Change' refers to large-scale change in the Earth's biological, geological, hydrological, and atmospheric systems, whether of natural or human origin. The Agricultural Research Service (ARS) conducts a strategic National Program entitled 'Global Change' because agriculture is vulnerable to environmental change and because agriculture can, in turn, affect some of the factors contributing to these changes. We have long recognized that short-term environmental changes at regional scales, such as seasonal drought and late freezes, are primary causes of variation in crop yield and livestock productivity. We need to address the likelihood that agricultural and other terrestrial ecosystems also will be affected by long-term global-scale changes such as human impacts on the Earth's atmosphere and energy balance. At the same time, we must investigate the potential for agriculture to play a role in mitigating the factors affecting environmental change, for instance by sequestering carbon in soil.

The Earth's atmosphere contains trace concentrations of several gases that absorb part of the radiation being reflected back to space, warming the 7-to-10 mile area above the Earth's surface called the troposphere. The principal absorbing gases are water vapor, carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. This 'greenhouse effect' is an important process that maintains temperatures near the Earth's surface within the range necessary for life, but there is concern that rising concentrations of these gases may be causing changes in climate. Chlorofluorocarbons are human-induced and were not present in the pre-Industrial Age atmosphere. Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased substantially since the beginning of the Industrial Revolution, about 200 years ago, also due to human activities. If current rates of emissions continue, atmospheric carbon dioxide levels are expected to double sometime within the next century. Scientists around the world have reviewed these effects on the climate in the Second Assessment of the Intergovernmental Panel on Climate Change (IPCC) in 1995. They concluded that global mean surface temperature has already increased between .5 to 1.0 degree Fahrenheit since the late 19th century, and projected, with understandable uncertainty, a further rise in global mean temperatures of about 3.5 to 7 degrees Fahrenheit by the year 2100.

Agriculture has played a role in these changes in atmospheric chemistry. Historically, carbon dioxide was liberated by conversion of forest and grassland to agricultural use. Studies have shown that soils of the Great Plains have lost up to 64% of their original organic carbon to the atmosphere as carbon dioxide. Currently, it is estimated that agriculture accounts for one-fifth of the annual increase in human-induced greenhouse warming. Much of this is due to methane and nitrous oxides; agriculture produces about 50% and 70%, respectively, of human-induced emissions of these gases. Like carbon dioxide, atmospheric methane concentrations have doubled in the last 200 years. Nitrous oxide is naturally emitted from soils, but the rate of emission increases when nitrogen is added as inorganic fertilizer or manure or through fixation by legumes. Nitrous oxides from agricultural soils represent approximately 25% of all U.S. noncarbon dioxide human-induced greenhouse gas emissions.

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

Program Components

The Global Change National Program focuses on four aspects of global change, and these aspects form the four components of this Action Plan**:** **Carbon Cycle and Carbon Storage**; **Trace Gases; Agricultural Ecosystem Impacts**; **and Changes in Weather and the Water Cycle at Farm, Ranch, and Regional Scales**. These factors may significantly affect agricultural productivity and are not addressed by other ARS national programs. Other environmental changes that might be considered part of global change include the depletion of the stratospheric ozone layer that is responsible for increased UV-B radiation, declining biological diversity, and deforestation. Land degradation due to poor management and widespread changes in land use patterns also are labeled global environmental changes. These aspects of global change are equally important but are addressed by the three national programs focusing on production systems (Food Animal Production, Crop Production Systems, and Integrated Agricultural Systems) and by four natural resource programs (Air Quality; Water Quality and Management; Soil Resource Management; and Rangeland, Pasture, and Forages). In fact, most of the Global Change National Program research is conducted in collaboration or conjunction with projects in one or more of the national programs noted above. The four components of the Global Change National Program are summarized below.

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

The overarching goal in this component is to provide the data and the process understanding necessary to describe the current and potential roles of agriculture in the global carbon cycle with sufficient accuracy to inform policy and aid producers in making decisions that are both economically and environmentally sound.

Trace Gases. Much has been learned in recent years about the role of agriculture in trace gas production, but much work remains. Recent research has shown that feed quality and digestibility dramatically affect the amount of methane produced by ruminants. Future research will focus on the management of pastures and rangelands to improve digestibility. In waste management, research has shown that dry storage of manure results in significantly less methane production than wet storage, yet the use of wet storage is increasing because it is more economical in large concentrated feeding operations. Research is necessary to eliminate this conflict between environmental and economic goals. We also know that better use of natural nitrogen sources, such as legumes, and less use of manufactured fertilizers should lead to lower nitrous oxide emissions. Research in this area will focus on developing cropping systems that manage nitrogen to minimize trace gas emissions while preserving productivity. Finally, research also will address the need for synthesis of information to provide larger scale estimates of agricultural emissions, which is currently difficult because of the lack of appropriate models and a shortage of data necessary to develop and test them at the appropriate spatial scales.

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

Changes in Weather and the Water Cycle at Farm, Ranch, and Regional Scales. General circulation models (GCMs) used to simulate climate responses to rising greenhouse gas concentrations predict that changes in precipitation will accompany rising temperatures. The models show that temperature and precipitation will not change uniformly across the globe but will vary regionally, meaning that some regions may prosper while others suffer. Changes in seasonal patterns of precipitation, such as a shift in the peak rainfall period, also could be important. Overall warming could have deleterious effects on agricultural water supplies in areas such as the Central Valley of California that depend on snowfall as a water source. Variability in weather also has the potential to affect agriculture. Some GCMs predict that variability will increase with global warming. The frequency and magnitude of large-scale atmospheric forces such as El Nino may be enhanced. Droughts, floods, and periods of excessive heat or cold may occur more frequently, and the frequency and severity of extreme weather events such as storms also may increase. Increases in extremes are viewed with concern because variation in weather, from cool, wet spring planting periods to extended summer droughts, is currently the most significant cause of instability in crop yields. Assessments also indicate that greater variability would increase crop insurance costs and disaster payments. Much of the research required to address these issues, because of their speculative nature, involves models. This research will include the improvement and use of weather generation models to examine the potential effects of increased variability. It also will address questions of scale mismatch in existing models. On the one hand, this will involve downscaling, so that the impact of GCMs on local water supplies can be examined, while on the other hand, it will entail development of methods to represent accurately local scale heterogeneity in larger scale models to improve their predictive capability.

Synthesis and Integration of Research Findings

In addition to the four research components outlined above, a critical need in global change science and policy is the integration of information on this complex subject from many different sources. The complexity of all the scientific issues considered part of global change, in conjunction with current needs for policy guidance, creates an immediate need to develop broad insight and conclusions from the scientific literature and databases. Results of nearly all research conducted by ARS scientists (including data and metadata) should be archived for wide use and, when appropriate, linked to or combined with data from other sources. However, the current need by the scientific community, policymakers, and the public for integrated synthesis of information concerning global change justifies particular attention to this as a special activity in the ARS Global Change National Program.

Publication of research in scientific journals alone cannot provide the insight or keep pace with the need for integrated information in the policy arena. New data, analyses, and models must be assembled from many different sources across the research community if scientific direction and policies are to based on the most current information. New developments are particularly rapid in the global change area. Decisions about public policies and research priorities will be made whether by guesswork or by informed expertise; ARS believes the latter is much preferred. ARS scientists are among the best qualified in the world to provide input to global change policy decisions, but reliance on journal publication of research is insufficient to contribute in a comprehensive and timely manner. Thus, ARS scientists participating in the Global Change National Program are encouraged to synthesize and integrate information from all sources, not just their own programs, as part of their activities.

ARS scientists will maintain an awareness of needs for policy development and scientific guidance through routine contacts with customers, stakeholders, National Program Staff, governmental and nongovernmental agencies, and the scientific community. ARS scientists and National Program Leaders will identify needs for information about global change that transcend the routine research and publication processes. The research planning process based on customer and stakeholder needs will help scientists identify these types of activities early in the life of a given project.

A recent book provides an example and a product of this kind of information synthesis and integration activity. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect (Lal et al., 1988, Ann Arbor Press, Chelsea, MI), was written by a team of scientists from a land-grant university, ARS, and the Natural Resource Conservation Service (NRCS). This team compiled data on soil carbon and management practices from many different sources to develop a concise, yet in-depth, analysis of the amount of carbon that could be removed from the atmosphere and stored in croplands. This analysis addressed the contribution of U.S. agriculture to the world s greenhouse gases and the extent to which American agriculture might mitigate the buildup of these gases. Data from many sources in the published literature were used. In other related activities, ARS scientists and their collaborators have used different types of models to examine the validity and implications of approaches to accounting for sequestered carbon under different types of land uses and management practices. This information, based securely on reliable data and scientific approaches, has been made available directly to policymakers as they have prepared for international discussions. ARS scientists will continue to be prepared to make important contributions to integrating and synthesizing information in new ways that enhance the value of published research; this activity is recognized as an integral aspect of the Global Change National Program.

The multidisciplinary nature of data and information required to understand the causes and impacts of global change requires an analytical effort to an extent never before attempted. Observations at multiple scales need to be integrated with models and then presented in understandable ways to all levels of the scientific community, government, and the public, so that the resulting knowledge can be used to adapt and mitigate appropriately in proportion to the risks present. This multidisciplinary analysis of environmental change at multiple scales involving satellite and in situ observations linked with models requires a highly advanced, distributed information system. To the extent practical and within Agency policies concerning availability of research data, ARS scientists and Program Leaders will pursue participation in public efforts to develop comprehensive databases, not just those inclusive of USDA data only, related to global changes. Data sets and metadata will be assembled, archived, and disseminated in appropriate formats, including web sites maintained by public agencies. Formats and media will be selected for the most appropriate use, accessibility, and impact for the public, government, and scientific communities. This is potentially an entirely new way for federal, state, and local governments; scientists; and the public to interact with each other and with data and information to provide insight into the global processes affecting the daily lives of people around the globe.

Vision

A productive and profitable future for American agriculture based on a research program that correctly anticipates changes and provides the tools for producers to adapt to them

Mission

Develop and provide adaptation, mitigation, and management strategies to the individual farm, ranch, and rural community, and to natural resource decision-makers to allow them to derive optimal benefit from the positive aspects of global change and deal effectively with the detrimental effects

Planning Process and Plan Development

An initial workshop for the Carbon Storage Component of the Global Change National Program was held in Baltimore, Maryland, on January 12-14, 1999. Approximately 50 participants attended, including producers, agricultural industry representatives, representatives of nongovernmental organizations, university scientists, and scientists and administrators from ARS and other federal and state agencies. At the workshop, our customers, stakeholders, and partners participated in discussions and provided input concerning problems and research needs in carbon storage. A subsequent workshop on the entire Global Change National Program was held in Denver, Colorado, on October 4-7, 1999. Approximately 120 participants attended, representing all groups of customers, stakeholders, and partners with an interest in global change research. They participated in two days of plenary sessions and breakout groups to identify and prioritize key research needs in the area of agriculture and global change. This was followed by a day of discussion by ARS scientists in attendance designed to incorporate the input of the stakeholders into this planning document.

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

The four principal research components listed above were identified. Writing groups were organized to address each of these components, and each writing group subdivided its component into three to eight problem areas based on the stakeholder input. The writing team used input from the workshops, their own knowledge of the subject matter area, and input from ARS scientists to identify problem areas. Each problem area then became the subject of a two-to-three page statement summarizing current knowledge, gaps, and objectives for use in developing planning documents that will frame ARS research. Relevant ARS research locations were identified for each problem area. The resulting matrices will be used to identify areas where additional research emphasis is needed and to develop detailed research and implementation plans. The problem area statements for each of the components were collated and organized by a writing team leader with iterative editorial suggestions from all contributing writers. The writing team leaders then convened with the National Program Leaders for the Global Change National Program in January 2000 to produce this document. The National Program Leader for Global Change is Steven Shafer, assisted by Michael Jawson (National Program Leader for Soil Biology), David Farrell (National Program Leader for Hydrology and Remote Sensing), Evert Byington (National Program Leader for Rangeland, Pasture, and Forage), and John Radin (National Program Leader for Plant Physiology).

Following a public comment period, this document will be revised, and the implementation phase of the process will begin. During the implementation planning phase, specific research areas will be identified, locations and projects involved will be determined, anticipated products or information generated by the research will be identified, and time lines and milestones will be developed to measure progress toward achieving the goals. This approach will result in coordinated, multilocation research projects, written and conducted by ARS scientists and their cooperators, to address high priority regional and national research needs. These research plans will be peer-reviewed, revised as necessary, and used to guide research at the identified individual locations. A 5-year assessment of the Global Change National Program will occur in 2004.

Table 1. ARS Locations contributing to the Global Change National Program

Global Change National Program Components

State	Locations	Carbon Cycle and Carbon Storage	Trace Gases	Agricultural Ecosystem Impacts	Changes in Weather & the Water Cycle at Farm, Ranch, and Regional Scales
AR	Booneville	X			
AL	Auburn	X	X		
AZ	Phoenix	X	X		
AZ	Tucson	X			X
CA	Fresno	X			
CA	Riverside	X			
CO	Akron	X			
CO	Ft. Collins	X	X		X
FL	Gainesville	X			
GA	Tifton	X			X
GA	Watkinsville	X			
IA	Ames	X	X		
ID	Boise				X
ID	Kimberly	X			
IL	Champaign	X			
IN	West Lafayette	X			
MD	Beltsville	X	X		X
ME	Orono	X			
MN	Morris	X	X		
MN	St. Paul	X			
MO	Columbia	X			
MS	Oxford	X			X
MS	Stoneville	X			
MT	Miles City	X			
MT	Sidney	X			
ND	Mandan	X			
NE	Lincoln	X	X		
NM	Jornada	X		X	
NM	Las Cruces				X
OH	Columbus	X			
OH	Coshocton	X			X
OK	El Reno	X			X
OK	Woodward	X			
OR	Corvallis	X			
OR	Pendleton	X			
PA	University Park	X		X	
SC	Florence	X	X		
SD	Brookings	X			
TX	Bushland	X	X		

TX	Temple	X		X	X
TX	Weslaco	X			
WA	Prosser	X			
WA	Pullman	X	X	X	
WV	Beaver	X			
WY	Cheyenne	X			

Action Plan:

Component I: Carbon Cycle and Carbon Storage

Introduction

Background

Carbon is the element that defines organic compounds, i.e., those derived from plants and animals, and is therefore at the core of life processes. It has been the object of a great deal of research, but much is still unknown about its cycling from the soil into the atmosphere and back into the soil. This cycle includes both organic and inorganic, i.e., derived from minerals, compounds. The increase in atmospheric carbon dioxide, a greenhouse gas, has heightened interest in carbon storage science because of the role of carbon dioxide and other carbon-containing compounds (methane and other hydrocarbons) in climate change. The concentration of carbon dioxide has increased in the Industrial Age from 270 parts per million (ppm) in the atmosphere in 1800 to the current 365 ppm. It is continuing to increase at a rate of approximately half a percent per year. The increase has been due partly to the burning of fossil fuels and partly to changes in land use and management, including deforestation, conversion of grasslands to croplands, and farming practices that accelerated oxidation, or breakdown, of soil organic matter.

Agricultural research has long focused attention on carbon cycling, primarily because of the fundamental role of carbon in plant development but also because of the importance of organic carbon compounds in maintaining soil tilth and productivity. Recently, in response to concerns about global climate change, a strong interest has developed in determining how agricultural activities and practices can be used to store carbon, particularly in soil. Scientific methodology to enhance soil carbon storage requires a holistic investigation of carbon cycle science. Soil carbon storage potential is the subject of both policy and scientific study. A federal multiagency research initiative on the carbon cycle, the U.S. Global Change Research Program Carbon Cycle Initiative, is under development to address carbon cycle science. ARS is participating in this initiative because agricultural activities have a major impact on the carbon cycle

Soil is the largest terrestrial global carbon pool, estimated to be about one-and-a-half trillion tons. This dynamic pool participates in an annual carbon dioxide exchange between the soil and the atmosphere 10 times as large as that emitted by fossil fuel use. In general, a balance is maintained between the carbon dioxide removed from the atmosphere by plants and the carbon dioxide returned to the atmosphere from the decomposition of plant and animal material. However, changes in land use and land management can disrupt that balance. When native forests and grasslands were cleared and plowed to grow crops during the westward expansion of the U.S., plant and soil organic carbon was rapidly decomposed to carbon dioxide; thus, cultivated agricultural ecosystems contributed to the increase in atmospheric carbon dioxide. On average, the carbon content of tilled soils in the U.S. has been reduced about 40% from pre-tillage levels. This historical loss now provides a pool that can be refilled by using management practices such as improved cropping systems, conservation tillage, grass buffers, and measures such as the Conservation Reserve Program (CRP) and wetlands. Soil carbon storage, then, could partially offset fossil fuel and other carbon emissions, at least until soil storage capacity is reached. Moreover, best management practices for both cropped and grazed lands improve soil resources while increasing carbon storage.

We need a better understanding of the dynamic path of carbon storage. The amount of carbon stored in the soil is determined by the balance of two processes--production of organic matter by terrestrial vegetation (photosynthesis) and decomposition (respiration) of organic matter by soil organisms. Each of these processes is controlled by physical and biological factors. For a given plant type, photosynthetic production depends largely on climate (solar radiation, temperature, rainfall), soil water status, nutrient availability, and carbon dioxide concentration, the latter providing a potential positive aspect of rising atmospheric carbon dioxide levels. Land use options for enhanced carbon storage include identification, protection, and selective management of the most productive native and agricultural ecosystems. Genetic improvements in vegetative photosynthetic capacities offer greater potential ecosystem capture of carbon dioxide and ultimate soil carbon storage.

Increased soil carbon storage is a co-benefit of conservation policies and efforts to reduce soil erosion on agricultural lands, which include the retirement of marginal or degraded croplands under the CRP and Highly Erodible Land conservation subtitles of the Food Security Act of 1985. This act allowed the voluntary retirement of more than 36 million acres of erodible lands for reseeding to perennial grass and tree covers. In addition, a projected two million miles of buffers along stream banks will be established to protect water from potential nonpoint source pollution. Key issues facing resource managers and policymakers are how to manage these vast resources for optimal economic returns while maximizing carbon stored under site-specific soil conditions and how to preserve much of the carbon pool upon termination of these programs.

Estimates indicate that each year in the U.S. about one-and-a third billion tons of carbon are removed from the atmosphere as carbon dioxide by the photosynthetic activity of agricultural crops. Furthermore, indications are that the North American continent is potentially a large repository for carbon. A portion of the fixed carbon within plants ultimately enters the soil, but the capacity of soils to store carbon, the length of time the carbon can be stored in the soil, and the rate at which carbon storage could be accomplished are matters of great interest to both scientists and policymakers. Because of the historical loss, there is no doubt that soil can serve as a carbon repository. Scientific studies have shown that proper management practices such as conservation tillage can increase soil carbon levels. The debate centers on the capacity of soils to store carbon while remaining in productive use and on the policies that will maintain agricultural productivity and maximize carbon storage and climate change benefits. If 5 -15% of the U.S. production of nonfood plant components in croplands were stored in soil organic carbon, an annual carbon storage rate of 70 to 200 million tons could be achieved. These are highly significant quantities of carbon, enough to store all the carbon dioxide emitted from agricultural activities and some of the fossil fuel emissions from other sectors of the U.S. economy. U.S. agriculture would be a net repository of greenhouse gases, helping to mitigate potentially harmful global changes.

Vision

Reduced risk of global climate change and enhanced soil resources through soil carbon storage research

Mission

Conduct and transfer the results of research to identify the best practices for storing carbon from atmospheric carbon dioxide in natural soil and plant systems to reduce greenhouse gases and enhance soil resources

Table 2. ARS locations contributing to the Carbon Cycle and Carbon Storage Component of the Global Change National Program

Global Change National Program Components					
State	**Locations**	**Carbon Cycle and Carbon Storage**	**Trace Gases**	**Agricultural Ecosystem Impacts**	**Changes in Weather & the Water Cycle at Farm, Ranch, and Regional Scales**
AK	Booneville	X			
AL	Auburn	X	X		
AZ	Phoenix	X	X		
AZ	Tucson	X			X
CA	Fresno	X			
CA	Riverside	X			
CO	Akron	X			
CO	Ft. Collins	X	X		X
FL	Gainesville	X			
GA	Tifton	X			X
GA	Watkinsville	X			
IA	Ames	X	X		
ID	Boise				X
ID	Kimberly	X			
IL	Champaign	X			
IN	West Lafayette	X			
MD	Beltsville	X	X		X
ME	Orono	X			
MN	Morris	X	X		
MN	St. Paul	X			
MO	Columbia	X			
MS	Oxford	X			X
MS	Stoneville	X			
MT	Miles City	X			
MT	Sidney	X			
ND	Mandan	X			
NE	Lincoln	X	X		
NM	Jornada	X		X	
NM	Las Cruces				X

OH	Columbus	X			
OH	Coshocton	X			X
OK	El Reno	X			X
OK	Woodward	X			
OR	Corvallis	X			
OR	Pendleton	X			
PA	University Park	X		X	
SC	Florence	X	X		
SD	Brookings	X			
TX	Bushland	X	X		
TX	Temple	X		X	X
TX	Weslaco	X			
WA	Prosser	X			
WA	Pullman	X	X	X	
WV	Beaver	X			
WY	Cheyenne	X			

Cropping System and Tilage

Problem Statement

Rationale. Agriculture can both impact and be impacted by global change. One of the major impacts is associated with greenhouse gas emissions. Cultivated agricultural ecosystems are a carbon dioxide emission source, with estimates suggesting that perhaps 40% of the pre-settlement soil organic carbon has been lost to the atmosphere. Agricultural soils are important in the global context not only because of the annual carbon dioxide exchange with the atmosphere but also because carbon storage in these soils is sensitive to management practices such as cropping systems and tillage. With improved conservation management practices, crop production systems also can become soil carbon repositories. However, the roles of tillage and soil erosion in carbon loss are not clearly understood because the erosion mechanics for transport of carbon and tillage-induced carbon loss have not been clearly identified. Agricultural conservation systems accomplish carbon storage relatively quickly and inexpensively and also buy time to develop new technologies to solve larger, long-term greenhouse gas emission problems.

What is known. Carbon can be stored in agricultural soils in organic or inorganic form, with the organic the most dynamic and complex. Higher amounts of carbon in soil enhance soil productivity, fertility, water-holding capacity, and other soil conditions that reduce erosion and control nutrient and pesticide availability and the release of these chemicals into the environment. Among practices that aid organic carbon storage are increased cropping intensity, conservation tillage, cover crops, crop rotations, and manure or other organic amendments. Estimates indicate that U. S. agriculture removes about 200 million tons of carbon as carbon dioxide from the atmosphere each year. A portion of the carbon within plants ultimately enters the soil, where a fraction of it may reside for hundreds of years, but the ability of the soil to store carbon over long periods of time and the rate at which it can be accomplished is a highly debated scientific question. Furthermore, recent measurements indicate that soil carbon can be rapidly lost following certain types of tillage.

Gaps. Key issues for the fate of global carbon dioxide are how the management of agronomic inputs impacts soil carbon storage; how the maximum potential carbon storage of a soil can be estimated; how long it takes to attain the storage potential; how long it resides; what the regional differences are; and how changes in the global environment, such as increased atmospheric carbon dioxide levels and weather patterns, impact soil carbon cycling. The role of plants with genetically modified physical and chemical attributes in soil carbon storage is unknown. The role of the carbon-to-nitrogen ratio of crop residue in greenhouse gas emissions and the dynamics associated with the equilibrium carbon-to-nitrogen value in a specific soil are not clearly understood.

Goals

- Define animal and cropping system effects, including tillage and residue management, on soil carbon storage, rates of soil carbon change, and carbon quality in different soils and climatic zones, including analysis of long-term experiments;
- Quantify inorganic fertilizer and organic byproduct effects on plant growth and soil carbon storage, rates of soil carbon change, and carbon quality in different soils and climatic zones;
- Quantify impacts of global change on soil carbon storage, rates of soil carbon change, and carbon quality in different soils and climatic zones;
- Define environmental and economic co-benefits of agricultural practices that reduce production risks, promote soil carbon storage, achieve agricultural profitability and sustainability, and improve soil productivity; and
- Develop monitoring protocols, sampling frameworks, and verification schemes to evaluate impacts of land use changes and management practices on greenhouse gas emissions and carbon storage and to document potential carbon credits in an emissions trading system.

Approach

Emphasis will be placed on measuring soil carbon storage and understanding carbon dynamics using an interdisciplinary, multidimensional approach that brings together physical, chemical, and biological processes and properties. As a baseline, existing experimental carbon data on crop production systems can be analyzed to determine the state of current knowledge on soil carbon storage in major U.S. agricultural lands. Methods must be developed to estimate upper limits of soil carbon storage by soil type, farming systems, eco-regions, and nationally to quantify potential reduction in greenhouse gas emissions attributed to agriculture. Existing carbon flux methods and networks (systems to measure exchanges of carbon dioxide between soil and the atmosphere) should be expanded to regions not currently covered and to other ecosystems and management strategies. Resulting data will be used to develop and test models that predict effects of shifts in cropping and tillage systems and land use changes on soil carbon input and storage.

Outcomes

- New and improved systems of management practices will promote and preserve stored soil carbon.
- Improved management will increase the amount and rate of soil carbon storage in grazed and cultivated lands.
- Conservation crop production will remain economically viable, meeting the food and fiber needs of a growing population, and will help reduce fossil fuel use and atmospheric carbon dioxide..
- Scientifically based information will be communicated to provide a solid foundation for national natural resource stewardship and energy conservation policies.
- Soil resources and air and surface and ground water quality will be enhanced.
- New tools for a wide range of spatial and temporal scales will lead to regional assessments of carbon and nitrogen fluxes which, in turn, will be used to quantify multiple environmental benefits of soil carbon storage and conservation agriculture.

Impact

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

Linkages to Other ARS National Programs

- Integrated Agricultural Systems
- Manure and Byproduct Utilization
- Soil Resource Management

Grazinglands, CRP and Buffers

Problem Statement

Rationale. Grazinglands (i.e., rangelands and pastures) and conservation seedings comprise grasslands that make up about 40% of the land area of the U.S. They contain large soil organic and inorganic carbon stores and are important because of their contribution to animal forage production and ecosystem health.

What is known. One of the concerns about the increasing atmospheric concentration of carbon dioxide is the effect on plant community-level responses in natural ecosystems. For example, in some instances, livestock grazing has enhanced carbon storage, but in some cases this increase has been at the expense of undesirable plant community shifts and reduced forage production, a trend that would continue under elevated carbon dioxide. Also, the recent invasion of traditional grasslands by shrubs, generally considered a negative change in the plant community, has been attributed by some to increased atmospheric carbon dioxide levels. This major change in the plant community may alter not only the amount of carbon allocated to below-ground processes, but also the distribution of carbon in the soil profile.

Gaps. We lack information on the potential capacity of grazinglands to store carbon and the rate of carbon accretion under various geographic and climatic conditions across the U.S. Key challenges include devising management schemes to maintain or enhance both grazingland production and carbon storage among diverse soil conditions and types. Management schemes should consider the effects of forage accumulation, grazing management, improved species, and fertility management. Under rangeland conditions, we need to consider the effects of stocking density and changing vegetation structure on processes and interactions that limit carbon storage potential, particularly during periods of stressed growing conditions.

Goals

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

Approach

Methodology and parameters in future data collection will be coordinated among locations to fill gaps in existing data on carbon storage in grazinglands, CRP, and buffers and to develop experiments. Existing carbon dioxide flux networks (systems to measure exchanges of carbon dioxide between soil and the atmosphere) should be expanded to regions not currently covered and to other ecosystems and management strategies. Tools must be developed and tested to estimate soil carbon storage in grazinglands, CRP, and buffers. These data then would be provided to develop and verify predictive methods describing the effects of ecosystem changes on soil carbon. Methods must be developed to predict changes in species composition, the range of altered ecosystems, and the resulting differences in potential carbon storage.

Outcomes

- Current and potential soil carbon storage will be estimated for various management and climate conditions.
- The rate of increase in atmospheric carbon dioxide will be reduced.
- Soil resources and air and water quality will be enhanced.

Impact

Enhanced quality of grazinglands, CRP, and buffer strips while attaining maximum potential carbon storage

Linkages to Other ARS National Programs

- Bioenergy & Energy Alternatives
- Food Animal Production
- Rangeland, Pasture, & Forages
- Soil Resource Management

Irrigation and Water Managment

Problem Statement

Rationale. Under the normal range of environmental conditions, water availability is the most limiting factor for production in crop agriculture, range or grasslands, and forests. Hence, production, and therefore short- and long-term storage of carbon in all managed plant environments, is influenced by any management factor affecting water availability and water use efficiency under both rainfed and irrigated conditions. Water availability and use efficiency can be increased through most cropping system components, including species and cultivar choice, tillage systems, mulching, weed control, rotational strategies and irrigation. Past focus has been primarily on yield or harvestable or forageable biomass production. Research is needed because of the potentially large impact of improved water availability and use efficiency on carbon storage and because management for this outcome is likely to differ from current practices for yield optimization.

What is known. About 85% of the cropped land area in the U.S. and a larger fraction of pasture, range, grasslands, and forests are solely rainfed (nonirrigated). In rainfed agriculture, water management is largely indirect, via choice and timing of various other cultural practices affecting the soil/crop water budget. For cropped land, these choices include selection of species and cultivar, planting dates, stand density, tillage regimes, weed control, mulching, surfactant use, fallowing, multiple cropping, root growth-enhancing practices, and various kinds of evapotranspiration management. Important factors for range and grassland are animal choice, vegetative species mix, stocking rates, grazing intensity or timing, and fire. Rainfed cropping system optimization can significantly increase yield and biomass production. It can either raise or lower soil carbon storage by specific effects on soil respiration and soil organic carbon oxidation associated with various facets of cropping system strategy. A substantial amount of the soil organic matter originally present in most American farmlands has been oxidized as a result of predominately conventional tillage-based farming, especially in areas where alternate-year fallowing was once common for nutrient mining and water accumulation. Original soil carbon equilibrium values can be attained or even exceeded on many of these soils through enhanced water management or combined with other cultural practices that conserve soil carbon.

Irrigated agricultural lands are an important U.S. economic and environmental ecosystem component, representing a potentially large dynamic and highly manageable repository for atmospheric carbon. Most irrigated agriculture in the U.S. is in arid or semiarid areas, where native biomass production is relatively low. Arid and semiarid soils also have relatively low native organic matter contents, typically 1-2%. The predominant environmental factor restricting native biomass production and soil organic matter accumulation on these lands is low amounts of useable annual precipitation. On typical arid or semiarid lands, biomass production increases 3- to 25-fold with irrigated agricultural husbandry, compared to native vegetation without irrigation. Depending on temperature regime, soil organic matter accumulation and hence, carbon storage, can be greatly enhanced by irrigation, especially where night and/or winter temperatures are low.

Gaps. Little is known about the effects of various water-impacting cultural practices on above- and below-ground carbon partitioning and/or long-term retention or loss of carbon stored in soil. Rangeland, grassland, and forest management for these considerations is less well researched than crop management. Irrigation of cool climate arid and semiarid lands has high potential for carbon storage above the native equilibrium values, but cropping strategies and management practices, especially irrigation scheduling criteria that balance yield, profit, and carbon storage, have not yet been undertaken. Many irrigation waters and soils are high in carbonates. The effects of irrigation scheduling and other cultural practices on both organic and inorganic sources of carbon are likely to be highly interactive. They may result in different carbon storage budgets compared to strategies developed solely on the basis of either organic or inorganic carbon storage under irrigation. Also to be considered are salt and specific ion accumulations possible with changes in irrigation strategies.

Goals

- Assess the impacts of direct or indirect management of rainfall and/or irrigation for crop, range, grass, and pasture systems on soil carbon storage to optimize the combination of yield, profit, and carbon storage;
- Quantify evapotranspiration from rainfed and irrigated crop, range, grass, and pasture management systems to achieve optimal water management, including irrigation scheduling for the best combination of yield, profit, and carbon storage; and
- Determine the interactions of organic carbon storage and inorganic carbon management in irrigated systems.

Approach

Field, greenhouse, growth chamber, and modeling studies will be conducted to determine the effects of major cultural practice options on indirect water management and consequent carbon storage effects. Given the large body of data on the effects of cultural practices on water availability and use for yield, market value of crops, and above-ground biomass production, a key focus will be to increase data on below-ground carbon effects from root growth, carbon compounds exuded from roots, and measured soil carbon changes. Once enough data are collected to provide reasonable links between above- and below-ground carbon relationships, modeling can take better advantage of existing data. New evapotranspiration data and irrigation scheduling relationships emphasizing links to soil carbon storage should be developed and data accumulated. Studies should be conducted to determine and extrapolate interactions between management strategies for combined carbon management in irrigated systems where large amounts of carbonates exist in the soil and in the irrigation water but where source repository relationships have not yet been determined.

Outcomes

- Improved water management in crop, range, grassland, and other vegetative systems will increase the amount of carbon storage that can be attained.
- Water management strategies, including irrigation scheduling criteria, for farmers, land managers, extension agents, consultants, government agencies, and policymakers will guide farming and land management practices, with accurate assessment of the potential magnitude of carbon storage.
- New water management tools, practices, and information will help meet carbon storage goals.

Impact

Increased carbon storage with optimized agricultural yield and profitability

Linkages to Other ARS National Programs

- Integrated Agricultural Systems
- Water Quality and Management
- Soil Resource Management

Plantation Tree Farming

Problem Statement

Rationale. Agronomically managed tree farms are important U.S. economic and environmental ecosystem components, representing a potentially large dynamic and manageable repository for atmospheric carbon.

What is known. Land management for plantation-style production of pulp and lumber has intensified in the past two decades, particularly in the U. S. Southeast and Pacific Northwest, on industrial and nonindustrial private woodlands. Increasingly, plantation-style woodlot management blurs the conceptual boundaries between agricultural and forestry practices and objectives. Tree farming also is being adapted as an integrated farming technique with intensive animal feeding operations to manage waste nutrients. Woodlot plantation practices routinely involve intensive fertilization, tillage, chemical weed and disease control, and irrigation, with practices tailored to specific soil, site, and system needs. Intensive management of forest and other tree species has increased yields of lumber, pulp, and other wood products. In irrigated Pacific Northwest poplar plantations, the planting-harvest cycle is as short as five years. In Southeastern Loblolly pine, rotation age wood fiber yields are typically doubled. Maintaining tree farm productivity through cycles of planting genetically superior seedlings and managing for enhanced growth with tillage, fertilization, irrigation, herbicide use, clear-cutting, and replanting, gives sustainable high yields over many cycles. Importantly, tree farming also increases short- and long-term carbon storage. Irrigated Pacific Northwest poplar plantations produce 49 tons of trunk and branch wood and 2 tons of leaves per acre by the 4^{th} year of production. Maintaining tree farm productivity increases the total amount of carbon that can be captured--in the short-term as paper and wood products and long-term as soil carbon from roots, exudates, and decomposed litter. Intensively managed tree farms have a high potential for storing carbon.

Gaps. Sound estimates of the total amount of carbon stored in intensively managed tree plantations are lacking, particularly the quantity and long-term fate or transformation of carbon in litter, below-ground tissues or exudates, and soil. Time scales associated with the fate of carbon in wood products need to be developed. This documentation will be critical for policymakers considering establishment of carbon credits for tree plantations.

Research to increase the productivity of highly managed tree farms is crucial, both to the economics of tree-producing enterprises and to the issue of long-term carbon storage. Land forms and soils that require tillage need to be identified, to include determining proper tillage practices and conditions (especially soil water) and developing specifically suited tillage equipment. Agronomic research is needed to identify management practice interactions to achieve optimal growth, including refining of site-specific management; potential use of animal, municipal, and industrial wastes; soil property requirements and impacts; and overall system productivity and ecosystem response. Virtually no reliable information exists on tree plantation evapotranspiration responses or irrigation requirements for scheduling to optimize selected system outcomes. One of the most critical gaps in tree farm management is in the areas of root response and below-ground carbon storage.

Goals

- Assess the impacts of intensive tree farm management on the amount and longevity of soil carbon storage by measuring the total amount of carbon stored in intensively managed tree plantations, including soil carbon changes and storage in below-ground tissues or removed as products.;
- Quantify evapotranspiration from rainfed and irrigated intensive tree farm plantations for key species and management systems to optimize water management for desired system outcomes;
- Quantify the carbon cycle time scales for all tree-derived products;
- Provide policymakers with accurate current data to establish carbon credits for tree farm plantations; and
- Address land owner/producer needs for broad reliable agronomic research to increase productivity, waste utilization, and below-ground responses, including carbon storage.

Approach

Existing data will be compiled and studied to synthesize an understanding of the impacts of intensive tree farm management on carbon allocation and to identify knowledge gaps. Simulations and field experiments, conducted in cooperation with industrial and other land owners/producers who are already practicing intensive tree farming, can be used to prioritize research and fill knowledge gaps. These field studies should quantify water, fertilizer, and other resource needs and should consider water quality issues as well as carbon storage. The data and new knowledge from these efforts can be provided to policymakers to quantify and explain the benefits of intensive tree farming as a basis for policy decisions to exploit the potential positive impacts of carbon storage.

Outcomes

- Reliable estimates will be made of the amount of carbon sequestered by intensive plantation forestry.
- Technology will be developed to quantify carbon cycle time scales for all tree-derived products and to determine the fate of carbon in tree-based ecosystem.
- A national carbon credit policy will reward landowners for maintaining sustainable, productive tree plantations that contribute to a healthy environment and public welfare.
- The Nation s tree farms will be more productive, meeting increasing demands for wood and fiber; increasing carbon storage to mitigate rising atmospheric carbon dioxide concentration; and allowing sensitive lands to be removed from traditional forest production.

Linkages to Other ARS National Programs

- Integrated Agricultural Systems
- Water Quality and Management
- Manure and Byproduct Utilization
- Soil Resource Management

Organic Carbon Transformations

Problem Statement

Rationale. Soil is the largest reservoir of carbon in terrestrial ecosystems. Understanding the mechanisms and processes involved in the accumulation and loss of stored soil carbon provides an opportunity to develop management strategies that increase carbon storage and decrease carbon loss.

What is known. Carbon is stored in the soil in both organic and inorganic forms. Neither the organic nor inorganic pools is homogeneous; both are composed of multiple compounds with a wide range of activity within the carbon cycle. Storage of organic carbon in the soil begins with the entrance of plant- and animal-derived material into the soil. Soil microorganisms control organic carbon cycling and storage in the soil by decomposing dead plant and animal matter and releasing carbon dioxide back to the atmosphere. Important factors regulating this microbial activity include the physical and chemical properties of the plant and animal materials entering the soil, the physical and chemical properties of the soil, and climatic conditions (e.g., temperature and precipitation).

Gaps. The above known factors need better definition as they relate to soil carbon storage. To enhance soil storage of organic carbon, we need to better understand the soil ecology (i.e., how the physical, chemical, and biological factors of the soil interact and affect each other). For example, soil aggregation processes contribute to the physical protection of soil organic carbon, but the relationship between the biological and chemical processes involved in soil aggregation is not well understood. Also needed is a better understanding of physical processes (e.g., erosion, fire, or leaching) by which organic carbon is lost from the soil.

Goals

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

Approach

We must use and assess new and emerging technologies to conduct basic and applied laboratory, greenhouse, and field research to fill identified knowledge gaps. Collaboration among research scientists is necessary to integrate research on the mechanisms and processes of carbon storage, model development, and the development of management practices to enhance soil carbon storage. Interdisciplinary approaches will be important in this research. Archived soil samples from previous studies can be reassessed to glean information on soil carbon changes related to specific long-term management practices. This effort also can benefit from literature searches of past studies on soil organic matter and soil carbon changes related to land use and management practices within land uses. Results of these searches can be used to assess the subsequent effects of these management practices on carbon storage potential. Adjacent sites with similar soil but known long-term differences in land use or management practices should be identified to allow comparison of differences in stored soil carbon.

Outcomes

- The uptake of carbon by plants will be increased, and improved strategies will be developed to store plant carbon as soil organic carbon;
- The amount of plant carbon stored as soil organic carbon will be increased through alteration of the quantity and quality of plant carbon in roots, root exudates, plant residue, and litter;
- The mechanisms and processes controlling uptake, decomposition, storage, and losses of soil carbon will be more predictable;
- Factors that control the production and turnover of various carbon pools under agricultural systems will be more predictable, which will contribute to useful approaches for storing carbon;
- Improved information will be made available on soil erosion, overland movement of carbon, losses of dissolved carbon, losses during burning, and losses from degraded and degrading soils; and
- Management strategies will be developed to protect soil inorganic carbon.

Impact

Enhanced soil and plant productivity with maximum soil carbon storage

Linkages to Other ARS National Programs

- Integrated Agricultural Systems
- Rangeland, Pasture, and Forages
- Soil Resource Management

Inorganic Carbon

Problem Statement

Rationale. Inorganic carbon, as calcium carbonate and dolomite, constitutes one of the largest carbon pools in the Earth's surface environment, comparable in magnitude to the organic carbon pool. In arid and semiarid irrigated regions, the soil inorganic carbon pool is usually several times larger than the organic carbon pool. The importance of inorganic carbon to the global carbon cycle is that it can serve as a long-term source or repository for atmospheric carbon dioxide, thereby affecting the atmospheric carbon dioxide concentration.

What is known. The interaction of agricultural practices and inorganic carbon is of major importance. Liming of soils (application of calcium carbonate) potentially can release significant quantities of carbon dioxide to the atmosphere, but in some instances also may serve as a repository. Irrigation practices, especially in arid and semiarid environments, may result in either carbon dioxide release to the atmosphere or storage of carbon, depending on various site- specific conditions, such as hydrological setting, irrigation and leaching efficiency, source of water, irrigation system, and nutrient management. Similarly, fertilizer and gypsum application impact inorganic carbon storage and release of carbon dioxide. Models exist to predict the carbon dioxide production and transport in the soil, thus the carbon dioxide concentration can be predicted as well. Models also exist to predict the soil solution composition and the amount of precipitation or dissolution of carbonate minerals in the soil. The predicted change in inorganic carbon and carbon dioxide release is related to the irrigation water composition, plant water uptake, and soil carbon dioxide content. These models have not been tested extensively to validate the predicted changes.

Gaps. We have no information on the changes in soil inorganic carbon as a result of agriculture and only rough estimates of the predicted impact of various practices on carbon release to the atmosphere. There is only limited, preliminary information on the impact of irrigation on changes in inorganic carbon and carbon dioxide emissions to the atmosphere. We can predict the long-term impact of liming on carbon release to the atmosphere but have no information or data on the rate at which it is released. We can predict the net effect of irrigation practices on carbon release, but such analyses have not been undertaken for specific locations, and the conclusions cannot be generalized to other irrigation basins or districts. Computer models are available to estimate the amounts of carbon release or storage under different management practices, but this information needs to be integrated into a hydrologic model where the transport of the water to either surface or deep aquifers is determined. Similarly, data on fertilizer applications are available, but there is no information about the interaction of the fertilizer and increased biological activity in the soil on the inorganic soil carbon.

Goals

- Determine the impact of major irrigation projects on inorganic carbon storage and emission of carbon dioxide to the atmosphere;
- Develop economically viable management practices that could either reduce carbon dioxide emissions from inorganic carbon or store carbon dioxide in the soil water system;
- Determine the rate and quantity of carbon dioxide released to the atmosphere as a result of liming and gypsum application and the effect of different management practices on that release; and
- Quantify the impact of different fertilizer products on the emission or storage of carbon relative to agricultural soils.

Approach

Soil cores will be collected at intervals over time in major agricultural regions from both cropped and disturbed sites and analyzed for inorganic carbon. The data will be used to calculate the changes in carbon storage and to determine the net effect on carbon dioxide concentrations in the atmosphere. Models then will be developed to predict carbon changes in present systems and to evaluate the impact of various management changes. Recommendations regarding carbon release will be evaluated in terms of other environmental consequences, such as efficient use of water and salt and nutrient loading to ground and surface waters. We also will measure residual inorganic carbon on limed fields and calculate carbon dioxide emission rates under different conditions.

Outcomes

New management practices on irrigated lands will reduce carbon dioxide emissions or facilitate storage of inorganic carbon in agricultural soils and hydrologic systems.

Linkages to Other ARS National Programs

- Water Quality & Management
- Soil Resource Management

Interactions of Carbon and Nitrogen Cycles

Problem Statement

Rationale. Most agricultural soils in temperate climates have lost significant amounts of original organic carbon because of excessive tillage. Conservation tillage practices that include reduced and no-tillage farming and increased cropping intensity, along with reseeding of marginal croplands to permanent cover, can increase soil organic matter and store a significant portion of the carbon released during the burning of fossil fuels. However, carbon and nitrogen cycles are linked such that storing carbon in soil requires inputs of nitrogen.

What is known. Several sources of nitrogen contribute to the soil nitrogen pool and can be available for incorporation into soil organic matter. Commercial fertilizer is a major source of nitrogen for conventional farming. Production of commercial fertilizer requires large amounts of energy and consumes fossil fuel. The effect of microbial activity on atmospheric nitrogen, associated with legumes for example, is a low input source of significant amounts of nitrogen. Animal wastes are an important source of nitrogen to the soil, but concentrating animals some distance from the production sites has created distribution problems. Rain and snow annually contribute a small amount of nitrogen to all terrestrial systems. Nitrogen in unharvested plant material is the largest single source of nitrogen returned to the soil in most cropping systems. The availability of this nitrogen for plant use depends on the carbon-to-nitrogen ratio and the quality of carbon in the plant residue. The wider the ratio and the more lignin tissue in the plant material, the slower the release of nitrogen during decomposition. The soil is a major repository for atmospheric methane, but ammonia-based fertilizer has been shown to interfere with methane oxidation.

Gaps. Increasing soil organic matter as stored carbon makes nitrogen less available for plant growth. There are economic and/or environmental problems associated with all available sources of nitrogen, and nitrogen transformations in the soil affect both the storage and release of soil carbon. Both the production and application of commercial nitrogen fertilizer require the use of fossil fuels, thus adding to atmospheric carbon dioxide. Legumes will not economically fit into all crop rotations; methods of increasing nitrogen fixation by free-living (neither parasitic nor symbiotic) microbes are poorly understood; animal wastes are concentrated in locations away from production areas; and deposition of nitrogen in precipitation is a small portion of crop needs. It is known that microbial oxidation of ammonia-containing compounds increases soil acidity, but the amount of acidification and the resulting carbon dioxide emissions have not been quantified.

Goals

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

Approach

Existing experimental data on use of legumes in crop rotations in different geographic and climatic areas will be analyzed to determine where it is feasible to incorporate legumes into crop rotations. Economic models will be used to determine where and when legumes can be used economically. Laboratory and field experiments will be conducted to determine how to encourage nitrogen fixation by free-living microorganisms, and laboratory and field experiments will be used to quantify the acidification that occurs from oxidation of organic nitrogen sources. Long-term research plots and natural systems in various climates will be examined to determine the extent and duration of interference by ammonia-based fertilizers with methane oxidation.

Outcomes

- New and improved management practices will promote the use of legumes or free-living nitrogen fixing microorganisms, reducing the need for fossil fuel based commercial fertilizer.
- The amount of soil carbon in cultivated lands will increase in response to increased cropping intensity and the availability of nitrogen.
- Soil acidification by nitrogen fertilizers will be reduced, decreasing the loss of inorganic carbon from applications of lime or from calcium-containing soils.
- Conservation practices will remain economically viable, meet the needs of a growing population, and will contribute to the reduction of fossil fuel use for food production.

Impact

Increased nitrogen availability to store carbon in the soil, improve soil productivity, and reduce fossil fuel use in food production

Linkages to Other ARS National Programs

- Integrated Agricultural Systems

- Rangeland, Pasture and Forages
- Soil Resource Management

Measurement, Validation and Modeling

Problem Statement

Rationale. To determine the soil's capacity to store carbon, it is critical to know the amount and rate of carbon exchanges between soil and the atmosphere. Carbon dioxide uptake by photosynthesis has been extensively researched. In contrast, the major limitation to understanding carbon exchanges, within the context of soil carbon storage, is the rate of carbon return to the atmosphere. Long-term conventional tillage of soils is known to deplete soil organic carbon below pre-cultivation levels. However, it is difficult to quantify and chart the time courses involved and to measure total carbon exchanges that result in soil carbon storage generated by land use and management practices.

What is known. A variety of meteorological, gas chamber, and carbon isotope techniques has been developed for measuring atmospheric and soil carbon interchanges and fluxes. Daily carbon dioxide exchanges can vary widely, with large uptakes of carbon by growing plants during the summer, and large emissions of carbon to the atmosphere in the fall as vegetation dies. Several models of carbon cycling in soil are available, although validation of key components has been hampered by lack of data and shortcomings in measurement technology.

Gaps. Most important to determining the amount of carbon stored in soils is the ability to measure soil carbon content and validate changes to that content over time. Adequate measurement of changes in soil carbon must include evaluation of the physical, biological, and chemical characteristics of soil organic matter and soil inorganic carbon. In addition, stabilities of various physical and chemical components of soil organic matter need to be evaluated. Measurement of changes in soil carbon storage must include sampling schemes that address the spatial and temporal variability of soil carbon; soil bulk density (weight per volume); and chemical, physical, and biological soil properties. We also need rapid analytical and field surveillance methods to extend our predictive capability of soil carbon storage and changes.

Thus far, concerns about changes in soil carbon have focused mainly on those resulting from biological processes; however, changes may result from soil inorganic carbon gains and losses caused by soil erosion, downward movement through the soil profile as dissolved organic or inorganic carbon, and burning. We need methods to estimate these abiotic losses.

Systematic methodologies to determine the impact of land use and management practices on soil carbon storage are needed to predict actual and potential soil carbon storage at local, regional, national, and global scales. Techniques and models are needed to estimate and predict soil carbon storage and storage potentials over similar land management areas from field to regional and national scales. Finally, models must be able to predict the concurrent impact of agricultural practices on both carbon dioxide exchange and the exchange of other greenhouse gases to assess the integrated effect on climate change.

Goals

- Develop tools and techniques to measure carbon exchange processes and to quantify soil organic matter, soil carbon, and soil nutrient (e.g., nitrogen) storage or loss for major agricultural ecosystems and
- Develop predictive tools (models) to understand, integrate, and predict the impacts of land use and management decisions and global change on soil carbon storage in agricultural ecosystems from the local to the national scale.

Approach

Field techniques, including micrometeorological methods and destructive sampling, will be used to measure carbon dioxide balances (increase vs. decrease) over representative landscapes for the long term. Soil sampling and chamber techniques will be used to determine land use and management-induced soil carbon losses. Emphasis will be placed on the development of new techniques to measure the physical, chemical, and biological changes in soil organic matter over time. Subsurface soil water sampling will be used to estimate convective losses of soluble carbon. Models will be developed and used to estimate soil carbon storage and storage potentials over similar land use and management areas and for scaling up from field to regional and national level estimates. This effort will include the use of remote sensing and geographical information systems.

Outcomes

- Tools will be developed to determine carbon budgets on short- and long-term time scales and on field-to-regional spatial scales.
- Standard techniques will be available to sample soils, determine bulk density, and analyze soil carbon.
- Methodologies will be developed to quantify the contribution of agricultural land use and management practices to soil carbon storage
- Precision and accuracy of soil carbon storage estimates will be improved.
- Techniques will be improved to assess changes in soil carbon pools resulting from abiotic processes such as erosion.
- Inventories of soil carbon for U.S. agricultural lands will be improved.
- Models and decision support systems will help to determine the specific amount, quality, and value of carbon storage for various agricultural land use and management practices.

Linkages to Other ARS National Programs

- Integrated Agricultural Systems
- Soil Resource Management

Action Plan:

Component II: Trace Gases

Introduction

Background

Climate change has been a natural feature of the Earth's past, and average global surface temperatures have varied from 5 to 7 ºC over glacial-interglacial cycles within the past few hundred thousand years. Although surface temperatures have increased by 2 ºC in the 10,000 years since the last ice age, the temperature has increased by 0.45 ± 0.15 ºC in the last century alone. Although linkage to human activities is controversial, much attention has been given to prediction of the climate effects of doubling the atmospheric carbon dioxide level, which is projected at current rates to occur by the middle of this century. Much of the discussion on global change has centered on rising carbon dioxide levels, but the combined effects of increases in other trace gases, such as methane and nitrous oxide, presently contribute almost as much to the greenhouse effect in the atmosphere as carbon dioxide

The atmospheric concentrations of greenhouse gases have risen significantly since the beginning of the industrial revolution. Methane, the most rapidly increasing greenhouse gas, has increased 145% since the beginning of the industrial revolution. Nitrous oxide and carbon dioxide have increased 15 and 30%, respectively, during this time period. Although these are the three major greenhouse gases emitted by industrial and agricultural operations, other gases exchanged by natural and agricultural ecosystems can indirectly affect atmospheric concentrations of greenhouse gases through their impacts on atmospheric chemistry and/or ecosystem functioning. These latter gases include ammonia, nitrogen oxides, nonmethane hydrocarbons, sulfur dioxide, and various organosulfur compounds.

Potential warming effects are not equal for all greenhouse gases, which has led to the adoption of an index called the Global Warming Potential (GWP). The GWP compares the potential warming effects of different trace gases relative to carbon dioxide. It combines the capacity of a gas to absorb infrared radiation, its residence time in the atmosphere, and the time over which climate effects are to be evaluated (usually 100 years). The GWP for each trace gas is calculated relative to carbon dioxide and is adjusted for any generation of secondary greenhouse gases formed from destruction of the primary gas. Methane and nitrous oxide have a GWP of 21 and 310 and equivalent atmospheric residence times of 12 and 120 years, respectively. In the short term (20 years), methane has a GWP of 60 and nitrous oxide of 280. It can be seen then, that larger percentage increases in the latter two gases can have a significant impact on global warming; however, the large increases in atmospheric carbon dioxide levels have been, and continue to be, the main contributor to infrared absorption or greenhouse effect, accounting for about 60% of the overall change. Since 1960, the effect of methane has only slightly increased, while nitrous oxide has made a progressively larger contribution to the greenhouse effect.

Three principal components comprise the human-induced GWP: fossil fuel combustion and transport, the chemical industry, and agricultural and land use changes (including deforestation). Fossil fuel combustion and transport are the major sources of the greenhouse effect and account for about half of the global GWP. Chemical products account for about 20%, but with the regulation and decrease of the halocarbons, this component has decreased in recent years. The agricultural sector accounts for about 20% of the global GWP. It accounts for about 50 and 75% of the human-induced methane and nitrous oxide, respectively, and a small portion (5%) of the carbon dioxide emissions. Deforestation and biomass burning, along with other land use changes, account for an additional 14% of the carbon dioxide emissions. The major contribution of carbon dioxide is within the equatorial regions, where emissions are due to biomass burning and decomposition and mineralization of soil organic carbon. Additional direct effects from agriculture result from ruminant animals, soil organic carbon decomposition from plowing and land cultivation, rice paddy cultivation, fertilizer application, use of manure, and drainage of wetlands.

Agricultural sources of trace gases that contribute to GWP include concentrated (e.g., feedlot) and diffuse (nonpoint source) emissions of methane, nitrogen oxides, and ammonia. These emissions are affected by production practices such as applications of water, fertilizers, and manures. Excessive use of chemical fertilizers can exacerbate nitrous oxide emissions, and ecosystem or land degradation decreases biomass productivity and reduces the repository capacity for carbon dioxide assimilation.

Worldwide, agricultural activity accounts for about 20% of the global GWP, but agriculture contributes only about 7% to the total U.S. GWP. Carbon dioxide and nitrous oxide emissions from fossil fuel combustion account for more than 84% of the U.S. GWP. About 31% of the total U.S. methane emissions are from agricultural activities. Domestic livestock production is the major agricultural source with 64% from enteric fermentation and 31% from manure management. The remaining agricultural source of methane is from rice production. Soil management and nitrogen fertilizer use account for 67% of the total U.S. nitrous oxide emissions.

Despite the relatively low contributions of U.S. agriculture to overall greenhouse effects, it is important that ARS investigate ways to reduce those contributions while maintaining a productive and profitable agricultural sector. Precisely identifying sources of emissions and developing effective mitigation strategies must be an initiative for all sectors of agriculture. Conservation tillage and other energy-efficient farming methods can reduce net fuel consumption; fertilizer use efficiency can be increased by reducing erosion losses, leaching, and volatilization; animal manures and waste disposal can be reduced by increasing animal feed conversion efficiency; methane emissions from ruminants can be reduced by feed and/or pasture improvement or feed additives; and other more efficient production systems can be developed to reduce trace gas emissions.

Vision

Productive crop systems that limit direct and indirect greenhouse gas emissions

Mission

Develop systems to reduce trace gas emissions from cropping and animal production systems

Table 3. ARS Locations contributing to the Trace Gas Component of the Global Change National Program

Global Change National Program Component II: Trace Gas					
State	**Locations**	**Cropping Systems**	**Enteric Fermentation**	**Waste Management**	**Rangelands & Pastures/Wetlands**
AL	Auburn	X		X	
AZ	Phoenix	X			
CO	Ft. Collins	X			X
FL	Gainesville	X			X
GA	Watkinsville	X	X	X	
IA	Ames	X		X	
ID	Kimberly				X
MD	Beltsville		X	X	
MN	Morris	X			
ND	Mandan	X			
NE	Clay Center			X	X
NE	Lincoln	X		X	
NM	Las Cruces				X
OR	Corvallis			X	
SC	Florence			X	
TX	Bushland	X		X	
WA	Pullman	X		X	
WI	Madison			X	
WY	Cheyenne				X

Cropping Systems
Problem Statement

Rationale. Croplands are a major source of nitrous oxide, contributing approximately 25% of total annual atmospheric input globally. Nitrous oxide, a direct greenhouse gas, arises from biological processes in the soil involved in transformations of nitrogen compounds derived from soil nitrogen mineralization and from nitrogen added as synthetic fertilizer, livestock manures, crop residue and nitrogen fixed through biological processes. Excessive or improperly managed nitrogen fertilization results not only in increased nitrous oxide emissions but also loss of other indirect greenhouse gases, nitric oxide and ammonia. Leaching and runoff of nitrate from cropped fields contaminates ground and surface waters and can lead to additional nitrous oxide emissions after this nitrogen leaves the agricultural system. Nutrient and water management also impacts emissions of methane, another important direct greenhouse gas, from rice crop production. As fertilizer use increases, improved management will be required to limit the continual increase in emissions of methane, nitrous oxide, nitrogen oxides and ammonia from crop production.

What is known . Methane, nitrous oxide, nitrogen oxides and ammonia are produced in the soil and sediments through natural biological processes. These processes occur naturally, and all leakage of nitrous oxide, nitrogen oxides, and ammonia cannot be eliminated. Current crop production practices typically involve relatively large nitrogen input to meet yield goals; about 11 million metric tons were used in crop production in the U.S. in 1997 in addition to an estimated 5 million or more metric tons from livestock manures and crop residue. Some cropping practices induce leakage of nitrous oxide, nitrogen oxides, ammonia, and nitrogen oxide while others promote more efficient nitrogen use and limit excess leakage. Adoption of management practices, including crop rotations, that promote recycling of crop residue and livestock waste to limit new synthetic nitrogen fixation will likely decrease greenhouse gas emissions and nitrate leaching. Finally, agricultural soils are not only a source of greenhouse gases; for instance, well-drained aerobic soils remove atmospheric methane via biological oxidation.

Gaps. We know a great deal about specific greenhouse gas production processes and general relationships of chemical, physical, and biological controls on these processes. However, we have limited ability to predict whole farm greenhouse gas budgets, either for individual gases or for all direct and indirect greenhouse gases in combination. Gaps in our knowledge that preclude field, farm, and regional assessment of greenhouse gas exchanges include, but are not limited to the following:

- Ability to assess trace gases from field to regional scales;
- Annual and seasonal variability relative to weather;

- Impact of tillage and crop rotations on trace gas exchange;
- Effect of residue management on trace gas exchange;
- Limited knowledge of below-ground processes on trace gases
- Impact of irrigation management practices;
- Impact of nitrogen input type and timing (synthetic and livestock);
- Limited knowledge of nitrous emissions from nitrogen applied to croplands and moved off-site by ammonia volatilization, nitrogen oxide emissions or nitrate leaching, or runoff;
- Whole-farm trace gas exchange;
- Effect of crop type and variety on trace gas emissions; and
- Role of riparian zones in trace gas emissions.

Goals

The overall goal of this research is to preserve environmental quality by limiting gaseous emissions of nitrogen and carbon compounds while maintaining crop production. To achieve this goal, specific research goals are to

- Develop productive management practices that minimize trace gas emissions;
- Quantify the relationship between soil carbon storage and trace gas flux;
- Provide information to improve national trace gas inventories;
- Quantify the role of buffer and riparian zones on trace gas exchange; and
- Quantify the impact of increasing carbon dioxide concentrations on trace gas exchange within crop production systems.

Approach

Interdisciplinary research is needed to assess impacts of management on total greenhouse gas budgets for carbon dioxide, methane, nitrogen oxides, nitrous oxide, and ammonia at the field, farm, regional and national scales. This research will require input from agronomic, natural, and physical scientists who utilize a variety of methods to measure, assess, and mitigate trace gas emissions. Management considerations should include tillage, irrigation, crop rotation, tightening coupling between livestock and crop production, and weather variability interactions. These methods, which include different measurement techniques as well as synthetic and analytical methods such as modeling, will need to be evaluated at the appropriate temporal and spatial scales. Further development of fundamental understanding will allow integration of measurement and modeling to guide improved management techniques that conserve nutrients and limit trace gas emissions.

Outcomes

- Improved measurement techniques
- Crop management systems that improve nutrient utilization and limit greenhouse gas emissions
- Decreased agricultural greenhouse gas emissions
- Seasonal and annual prediction capability for the various gases
- Improved national inventories of trace gases

Impact

Decreased greenhouse gas emissions without adverse effects on productivity

Linkages to Other ARS National Programs

- Manure and Byproduct Utilization
- Soil Resource Management
- Water Quality and Management

Enteric Fermentation

Problem Statement

Rationale. Methane is the most abundant organic gas in the Earth's atmosphere, and evidence has shown that methane concentrations have increased globally at a rate of about seven-tenths of a percent per year from 1984 to 1994. Methane affects the atmosphere in several different ways, including effects on carbon monoxide concentrations and ozone. In addition, because of its greenhouse effect properties, it also affects the Earth's energy balance. Human-induced sources account for about 70% of the total annual production or release of methane. In turn, enteric fermentation in domesticated ruminant animals accounts for about 16% of the human-induced release.

What is known. Most estimates of methane production by ruminant animals are based on models using careful measurements from concentrated animals in respiration-chamber experiments conducted to assess the energy value of feeds. However, recently developed techniques using tracers and micrometeorological mass difference techniques now allow studies to be performed in pastures. This research has shown that when the cattle are grazed on conventional pasture, they convert about 8% of their gross energy intake into methane. When the same cattle were fed a highly digestible, high grain diet, the figure fell to about 2%. These measurements clearly document that cattle receiving low-quality, high-fiber diets produce about four times as much methane. Preliminary studies have shown the effectiveness of nutrient management in reducing methane emissions under grazing conditions.

Gaps. A number of compounds may be used to reduce the production of methane in the rumen. Temporal effectiveness of these compounds is unknown, and controlled-release application techniques for sustained periods are not currently available. Given the wide variation in feedstuffs and animals around the world, we need to assess the applicability of technologies to reduce methane emissions while increasing productivity.

Goals

The overall goal of this research is to minimize methane gas emissions while maintaining productivity. Specific research goals are to

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

Approach

Interdisciplinary approaches will be used to evaluate methods to reduce emissions, such as through feedstuffs quality and chemical additives. Avenues of research will include

- Testing a family of compounds for use in reducing methane production. Extensive grazing studies will be established to determine the long-term methane-reducing potential of these compounds.
- Studying the use of feedstuffs with varying rates of nitrogen availability to stabilize rumen nitrogen levels for improvement of fermentation efficiency.
- Evaluating supplemental compounds for use as alternative hydrogen acceptors to prevent the formation of methane production (e.g., unsaturated fats such as in whole cottonseed).
- Evaluating combinations of the above three treatments in addition to the individual studies.

Once appropriate technologies are developed, appropriate stakeholders will be involved in assessing increased industry efficiency from reduced energy loss, producer acceptance of improved management strategies, and consumer endorsement of 'environmentally-friendly' animal production systems.

Outcomes

- Methane emissions will be reduced.
- Animal feedstuff efficiency will be increased.

Impact

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

Linkages to Other ARS National Programs

- Food Animal Production
- Manure and Byproduct Utilization

Waste Management

Problem Statement

Rationale. Animal waste is a source of both methane and nitrous oxide emissions. Emissions from animal waste account for about 30% of the total U.S. methane emissions from agriculture. Soil application of manure can produce nitrous oxide through the microbial processes of mineralization, nitrification and denitrification.

What is known. Composition and digestibility of animal feed affect methane emissions. The greater the energy content and digestibility of the feed, the greater the methane-producing potential of the manure. The actual quantity of methane emitted, however, depends primarily on the manure management system. Manure stored in dry pits or deposited on pastures or rangelands decomposes aerobically and produces little or no methane, but the trend in the U.S. has been to larger herd sizes and cost-effective liquid manure and disposal systems. These are oxygen-deficient (anaerobic) management systems and may significantly increase methane emissions.

Current methane emission estimates are based on the methane-producing potential of manure and on methane emission factors established in Europe and modified to U.S. conditions. For nitrous oxide, emissions from soils are closely related to soil conditions such as water content and available carbon and to the use of nitrogen fertilizers. However, current estimates are based on the assumption that 1.25% of fertilizer nitrogen applied is lost as nitrous oxide directly from agricultural fields. This may be high for some fertilizer management systems and may be low for animal waste applications because of the water and carbon often added with manure applications. Also, ammonia may be transmitted off-site as a gas or aerosol and may contribute to further nitrous oxide losses.

Gaps. Estimates of emissions from the methane-producing potential of manure, including estimates for different manure systems, need to be developed with direct on-site measurement of methane emissions. Separate estimates for synthetic and organic nitrogen fertilizers would provide more accurate estimates of nitrous oxide emissions. Limited information is available on emissions and transport of ammonia from animal and cropping systems in the U.S.

Goals

- Minimize greenhouse gas emissions while maintaining effective utilization of animal waste in agriculture;
- Improve the nitrous oxide emission coefficient estimate for manure-fertilized soils; and
- Quantify methane and ammonia emissions produced by manure under different management systems.

Approach

An interdisciplinary approach must be used to evaluate emissions from land application of manure. Studies will evaluate emissions as a function of relevant soil variables under different cropping and environmental conditions. Measured methane emissions rates from commercial farms using anaerobic treatment systems will be compared to rates estimated using current U.S. Environmental Protection Agency (EPA) methodology.

Outcomes

- Emission coefficient and conversion factors for animal waste management systems used in the U.S. will be more specific.
- Nutrients in animal waste will be more fully utilized to decrease greenhouse gas emissions.
- Estimates of agricultural methane's contribution to greenhouse gas emissions in the U.S. will be more accurate.
- Soil resources will be improved through more efficient use of nutrients in animal waste.

Impact

Decreased production of greenhouse gases in animal feeding operations

Linkages to Other ARS National Programs

- Food Animal Production
- Manure and Byproduct Utilization
- Soil Resource Management

Rangelands, Pastures adn Wetlands

Problem Statement

Rationale. Grazinglands in the U.S. occupy about 840 million acres, compared to about 380 million acres of cropland. They encompass a broad variety of soils and climates and serve as both a source of and repository for the greenhouse gases carbon dioxide, methane, nitrous oxide, nitrogen oxides, and ammonia. Grassland soils typically produce a low background level of nitrous oxide and nitrogen oxides. However, because of the vast area that produces them, the emissions can be a significant part of the U.S. atmospheric nitrous oxide budget. These soils also generally consume atmospheric methane and fix more carbon dioxide than they emit. Again, because of their large area they consume enough methane to be important in the global methane budget. Potentially, management of stocking rates in rangelands and pastures and nutrient management in pastures can promote system sustainability while limiting greenhouse gas emissions.

What is known. Management of rangelands and pastures can directly influence the amount and even the direction of the soil-atmosphere exchange of carbon dioxide, methane, nitrous oxide, and nitrogen oxides. Climate also plays an important role in the quantity and timing of production and consumption of these gases. For example, in a humid climate, nitrous oxide emissions from livestock urine patches are relatively large for days to months after deposition, while in a semiarid climate, emissions are relatively lower during the first year after deposition but remain higher for years to decades. Although pastures are typically only small sources of nitrogen oxides and nitrous oxide and potential repositories for carbon dioxide and methane, fertilizer management and stocking intensity can change the pastures into large sources of nitrous oxide, nitrogen oxides, and methane while increasing the repository for carbon dioxide. Wetlands are typically sources of methane but repositories for carbon dioxide and emit relatively little nitrous oxide and nitrogen oxides. Draining of wetlands can convert them into sources for nitrous oxide, nitrogen oxides, and carbon dioxide while decreasing methane emissions. Changes in climate will require changes in management strategies that will, in turn, impact both grazing system sustainability and greenhouse gas exchange.

Gaps. While we know a great deal about specific greenhouse gas production processes and general relationships of chemical, physical, and biological controls on these processes, we have limited ability to predict whole grazing system greenhouse gas budgets, either for individual gases or for all direct and indirect greenhouse gases. Gaps in our knowledge include, but are not limited to the following:

- Ability to assess trace gases from field to regional scale;
- Impact of annual and seasonal weather variability;
- Impact of irrigation management practices;
- Impact of nitrogen input type/timing (synthetic and livestock);
- Spatial and temporal variability of gas flux needed for scaling
- Limited knowledge of nitrous oxide emissions from nitrogen applied to croplands but moved off-site by ammonia volatilization, nitrogen oxide emissions, or nitrate leaching or runoff;
- Whole-system trace gas exchange (carbon dioxide, methane, nitrous oxide, nitrogen oxides, ammonia) in relation to grazingland carbon storage;
- Impact of nutrient management and grazing intensity on pasture production and trace gas exchange;
- Impact of wetland management on trace gas exchange;
- Role of riparian zones in trace gas emissions; and
- Impact of rising atmospheric carbon dioxide concentrations on rangeland sustainability and trace gas exchange

Goals

The overall goal of this research is to ensure sustainability of rangelands and wetlands and to maintain productivity of pastures while limiting gaseous emissions of nitrogen and carbon compounds. To achieve this goal of preserving environmental quality while enhancing sustainability of native systems and productivity of managed grazing areas research goals are to

- Develop management practices that limit trace gas emissions while maintaining productive use of grasslands. Management considerations should include irrigation; nutrient inputs and stocking rates and timing in pastures; stocking rates and timing in rangelands; and climate and weather variability interactions;
- Quantify the relationship between soil carbon storage and trace gas flux;
- Provide information to improve national trace gas inventories;
- Quantify the role of buffer and riparian zones on trace gas exchange; and
- Quantify the impact of increasing carbon dioxide concentrations on trace gas exchange within rangeland ecosystems.

Approach

Multidisciplinary research is needed to assess impacts of management on total greenhouse gas budgets for carbon dioxide, methane, nitrogen oxides, nitrous oxide and ammonia at the pasture, ranch, farm, regional, and national scales. Input will be needed from the agronomic, range, natural, and physical sciences with a variety of methodologies to measure, assess, and mitigate trace gas emissions. These methodologies, which include different measurement techniques as well as synthetic and analytical methods such as modeling, will need to be evaluated at the appropriate temporal and spatial scales. Further development of fundamental understanding will allow integration of measurement and modeling to guide improved management techniques that promote grazingland sustainability and limit trace gas emissions.

Outcomes

- Agricultural greenhouse gas emissions will be reduced.
- Measurement techniques will be improved.
- Management practices will be developed to limit greenhouse gas emissions from pastures and rangelands.
- Seasonal and annual prediction capability for the various gases will be improved.
- National inventories of trace gases will be improved.

Impact

Decreased greenhouse gas emissions without adverse effects on range and pasture lands

Linkages to Other ARS National Programs

- Rangeland, Pasture, and Forages

Action Plan:

Component III: Agricultural Ecosystem Impacts

Introduction

Background

The steady rise of greenhouse gases (carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons) has been well documented. Although debate continues about the potential long-term impact of rising greenhouse gases on global surface temperatures, direct instrumental data since 1900 and reconstructed earlier temperature records indicate that temperatures are currently rising. In addition, stratospheric ozone, which filters some UV-B radiation, has decreased somewhat due to destruction by chlorine monoxide released from chlorofluorocarbons in the stratosphere, so that UV-B radiation received at the Earth's surface has increased. The loss of stratospheric ozone is also enhanced by bromine, some of which may originate from manufactured methyl bromide. Conversely, increased ozone levels from human activities can damage leaves and reduce crop productivity. The overall effects of these extremely important climatic changes on agricultural ecosystem health and productivity are the subject of this component.

Global change impacts are not intrinsically negative. Increases in atmospheric carbon dioxide concentration benefit crops by increasing photosynthesis and productivity. Indeed, greenhouse producers throughout the world routinely fertilize high-value horticultural crops by artificially increasing greenhouse carbon dioxide concentrations. USDA research has shown that field crops also are more productive when exposed to higher carbon dioxide concentrations. Higher carbon dioxide also favorably affects plant water relations. Stomates, the pores in leaves through which plants gain carbon dioxide and lose water, respond to higher carbon dioxide by partially closing. Plant water use thus tends to decrease as atmospheric carbon dioxide concentration rises, resulting in increasing water use efficiency (the amount of mass produced per unit of water use), a potentially important benefit as nonagricultural demands for water increase.

Other aspects of global change may carry both positive and negative implications. Rising temperatures will likely favorably impact regions of the country with limited growing seasons, but may exacerbate problems associated with heat and drought stress in other regions. Temperature will also affect insect, weed, and disease pressures, although our knowledge of these effects, particularly their interaction with the effects of other expected changes, is insufficient at this time to predict overall impact. The combined effects of changes in temperature and precipitation patterns will likely cause shifts in the geographical distribution of both crops and native vegetation.

The most important questions, and those most difficult to answer, concern the overall integrated effects on agroecosystems of simultaneous changes in multiple factors. Most research to this point has understandably focused on one variable at a time, but there is no reason to believe that the underlying physical and physiological relationships can be considered separately. Design and execution of experiments with multiple variables is difficult under the best conditions and exceedingly so when the expected range of input variables must be extracted from the output of climate models that contain an unknown but presumably substantial uncertainty. However, uncertainty is no excuse for inaction. Today's climate models are much better than yesterday's, and further improvements are sure to come. As predictions improve, it is incumbent on agricultural scientists to conduct the research necessary to further reduce the uncertainty in our own domain. As the man being chased by the bear said, 'I don't have to be faster than the bear, but I'd better be faster than the guy that's next to me.'

Vision

Healthy, productive agroecosystems that successfully respond to a changing environment

Mission

To provide the knowledge necessary to foresee the impacts of global change on agricultural ecosystems, and to develop successful strategies and practices to adapt to change and improve productivity.

Table 4. ARS Locations contributing to the Agricultural Ecosystem Impacts Component of the Global Change National Program

Global Change National Program Component III: Agricultural Ecosystem Impacts				
State	**Locations**	**Cropping Systems**	**Grazinglands (Range and Pastures)**	**Pests**
AL	Auburn	X		
AZ	Phoenix	X		
CO	Ft. Collins		X	
FL	Gainesville	X		
GA	Watkinsville	X	X	
IL	Champaign	X		
MD	Beltsville	X		X
MN	Morris	X		
MN	St. Paul	X		
NC	Raleigh	X		X
NM	Jornada		X	X
OK	El Reno	X	X	
PA	University Park		X	
TX	Temple		X	
WA	Pullman	X		
WY	Cheyenne		X	

Cropping Systems
Problem Statement

Rationale. Global changes, especially climate change, could adversely impact crop processes and productivity. Therefore, research is needed on effects and interactions of elevated carbon dioxide, temperature, water availability, ground-level ozone, and UV-B radiation on crop production under different management systems. The ultimate rationale for cropping systems research is to maintain food and fiber production while sustaining economically viable farming systems across communities and regions in the face of climatic changes and shifts in land use.

What is known. Crop plants usually respond well to elevated carbon dioxide, with seed yields of many plants increasing about 30-35% with a doubling of carbon dioxide. Plants that possess the more efficient photosynthesis processes show less response (about 10-15%). The partitioning of growth to roots compared to shoots is increased in many cases, but not in all. Stomatal conductance (exchange of gases through microscopic pores in leaf surfaces) of most plants is decreased about 25 to 40% with a doubling of carbon dioxide. However, because of energy balance feedback effects, whole crop canopy evapotranspiration may be decreased only about 10%. Some studies have shown strong positive carbon dioxide X temperature interactions on yield (e.g., yield response to carbon dioxide increased linearly with rising temperature), while others report no effects or a slight negative effect. For many cereal crops and grain legumes, seed yields decrease sharply as temperature increases above an optimum of about 80 degrees Fahrenheit. Seed yields and seed quality decrease even though total biomass (vegetative material) productivity is maintained at higher temperatures until a failure threshold is reached. Nitrogen content and leaf quality frequently decrease as carbon dioxide concentration is increased. Recently, it has been shown that the primary enzyme (RuBisCO) involved in carbon dioxide fixation, may be under the direct control of carbon dioxide concentration. The messenger RNA for the synthesis of the enzyme changes rapidly down or up in response to increasing or decreasing carbon dioxide concentration, so that less of the enzyme is produced as carbon dioxide increases. Crop foliage health and seed yield may decrease in response to factors such as tropospheric ozone or UV-B radiation. Elevated carbon dioxide may protect leaf foliage from excess ozone. Some experiments indicate that a high carbon dioxide-low ozone environment may promote low harvest index in soybean.

Gaps. The sensitivity of seed yields to elevated temperature needs to be fully understood, and the potential for genetically modifying these crops needs to be explored to design future cultivars. Furthermore, the genetic control of the content of the enzyme RuBisCO needs to be determined so that genetic adaptations can be implemented to avoid loss of leaf quality (i.e., decreased soluble protein content) as atmospheric carbon dioxide rises. Furthermore, the impact of carbon dioxide and other climatic change factors on seed/grain and forage/residue quality is not well known. The mechanisms of the response of these plants to elevated carbon dioxide are not known. Multiple interactions of carbon dioxide concentration with high temperature, drought, ozone, UV-B radiation, weed competition, insect, disease, and nematode pressures under different management systems are not well known. Progress has been made on synthesis and integration with models, but more reliable general predictors are needed.

Goals

- Measure and predict plant responses (above and below-ground) to multiple interactions of abiotic and biotic stresses with rising carbon dioxide;
- Develop physiological criteria for improvement of crop quality (including leaf/forage/residue quality) of plants grown under elevated carbon dioxide; and
- Determine the causes for sharp decreases in seed yield and quality with increasing temperature, and develop suggestions for genetic modifications for improving yields.

Approach

An interdisciplinary approach will be used to assess the impacts of elevated carbon dioxide, temperature, water availability, ozone, and UV-B radiation on the quality and quantity of seed and forage crops. The full range of specialty field and lab facilities will be used--open-top chambers, closed-cycle SPAR chambers, FACE systems, controlled-environment linear array tunnels, and temperature-gradient controlled greenhouses.

Expertise of molecular biology, plant physiology, crop science, soil science, micrometeorology, control-process engineering, and computer modeling will be assembled to measure, predict, and assess plant responses to a whole range of abiotic and biotic factors generated by global change. Emphasis will be on experiments conducted with control of independent variables including multiple factors so that interactions of responses associated with global change can be assessed.

Outcomes

- Crops will use carbon dioxide more efficiently.
- More accurate general circulation models will better predict global climate under future altered greenhouse regimes.
- New management strategies will maximize benefits and minimize adverse impacts of elevated carbon dioxide and other global change factors.

Impact

More sustainable crop production systems

Linkage to Other ARS National Programs

- Air Quality
- Bioenergy and Energy Alternatives
- Crop Production
- Integrated Agricultural Systems
- Plant Biological and Molecular Processes
- Soil Resource Management
- Water Quality and Management

Grazinglands (Range and Pastures)

Problem Statement

Rationale. Rangeland agroecosystems occupy vast portions of the United States, occupying approximately 40% of the landscape. Vegetation is varied, including grasslands, shrublands and some woodlands. Although not as productive as more intensively cropped lands, rangelands are important to local and regional economies, and may represent an important reservoir of terrestrial carbon. Grazing these lands with domestic livestock is an efficient economic practice for utilizing this resource that results in food and fiber production for a burgeoning world population. Global change is expected to have important impacts on rangeland ecosystems, including changes in species composition of plant communities, primary production, and secondary animal production. Similarly, rangelands will likely be important in their exchange of carbon with the atmosphere.

What is known. The biological diversity of rangeland ecosystems may facilitate their adaptation to global change. The species distribution of rangeland vegetation and its productivity are determined, to a large extent, by seasonal water availability. By itself, increases in atmospheric carbon dioxide concentrations lead to improved water-use efficiency of rangelands and will result in increased primary production. Because some species are more sensitive to carbon dioxide, a change in plant community structure may also result (e.g., a shift from warm-season grasses to N-fixing shrubs). Forage quality of rangeland vegetation may change due to altered soil nitrogen availability and direct plant metabolic responses to carbon dioxide, both of which will affect the digestibility by herbivores and the cycling of carbon and nitrogen. The combined effect of increased temperature and altered precipitation patterns will likely impact rangelands by altering hydrology. Warmer temperatures will increase growing season length, but will have also increase evapotranspiration, leading to dessication. Predicted increased storm intensity may increase runoff and reduce the available water for plants. The judicious management of rangelands, primarily through varied domestic animal grazing practices, offers many options for optimizing agricultural practices to new environments and adapting to global change, including the potential for increased carbon storage.

Gaps. Knowledge of the integrated responses of North American rangelands to the combined effects of atmospheric carbon dioxide enrichment, warming temperature, altered precipitation patterns, and grazing practices is limited. Because only a small number of global change experiments have been conducted on rangelands, our understanding of how these vast and complicated regions will respond to global change depends on a synthesis of knowledge obtained from a relatively small number of disparate data sets, obtained under a variety of conditions and ecosystems. Little work has been done to evaluate how domestic livestock will respond and adapt to global change, particularly changes in forage quality and plant community composition. The ecology of new rotational grazing systems is poorly understood, as are the consequences of these systems for adapting to global change and their effect on carbon cycling, carbon storage, and biodiversity.

Goals

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

Approach

Because global change occurs over large temporal and spatial scales, the research should involve analysis of complex ecosystem responses. Combined and integrated experimental and modeling efforts will be conducted to develop successful management systems. Experimental studies will continue to focus on how rangelands respond to global change, but more emphasis will be placed on understanding the whole carbon cycle and its response to both global change and management. Possible mitigation strategies involving management effects on carbon storage will be explored.

Outcomes

- Predictions will be possible as to which rangelands will most respond to global change, including regions that may be susceptible to deleterious responses.
- Management strategies will be developed to take advantage of global change.

Impact

Healthy, productive rangeland ecosystems that successfully adapt to global change

Linkage to Other ARS National Programs

- Soil Resource Management

Pests

Problem Statement

Rationale. Changes in greenhouse gas concentrations and potential changes in climate will have a significant effect on crop systems and their associated pests, since the distribution and proliferation of weeds, pathogens and insects are determined to a large extent by climate. In addition weeds, like crops, are primary producers and will be affected directly by increases in atmospheric carbon dioxide. An understanding of these effects is crucial for maintaining agricultural productivity in the face of global change

What is known. In addition to stimulating growth and increasing water-use efficiency in plants, increasing carbon dioxide will stimulate photosynthesis and growth in most weedy species of plants and will reduce stomatal aperture and increase water-use efficiency in weeds. In addition, increasing carbon dioxide appears to reduce the efficacy of widely used post-emergent herbicides.

Many of the worst weeds in temperate systems originated from tropical regions, and their distribution is limited by low temperature. Depending on the extent of global warming, such weeds could extend their range northward. Increasing carbon dioxide also may increase the tolerance of certain weeds to sub-optimal temperatures, which also could expand their northward range. Partly because of increases in water-use efficiency under elevated carbon dioxide, weeds are expected to become more competitive in drier habitat.

Insect pests in agricultural systems are the second major cause of damage to yield quantity and quality, after weeds. Direct effects of carbon dioxide on plants can either benefit or harm insects, depending on their feeding habits. For example, pollinators could respond positively if more nectar is produced at flowering, with subsequent increases in fruiting. Conversely, higher carbon dioxide decreases the nitrogen content of foliage, which stimulates the feeding of certain insects such as the soybean looper and leaf miners.

Climate affects the range and distribution of insect pests through changes in minimum and maximum temperature, water availability, and other factors. Insects are sensitive to year-to-year differences in climate with large variations in population size and distribution. Consequently, absolute changes in any climate variable, the time rate at which the change occurs, and the frequency of extreme events can fundamentally alter insect ecology. Destabilization of insect habitats will result in increased migration as insects move to new locations to satisfy their ecological requirements. As a result, climatic change is likely to increase the range and distribution of agricultural pest infestations.

Almost no data are available concerning whether carbon dioxide could directly affect diseases or spread of fungi, bacteria, or viruses. Studies have shown that fungal infection increases with increased water content of plant tissues. Consequently, carbon dioxide-induced increases in water-use-efficiency could increase the occurrence of fungal infections. Overall, carbon dioxide enrichment could modify susceptibility to pathogen attack because of carbon dioxide-induced changes in the biochemistry or structure of the host plant.

The growth and rate of increase of crop pathogens will depend on temperature, precipitation, humidity, radiation, wind direction and the occurrence of extreme events. Higher temperatures and precipitation are conducive to the spread of plant diseases since hot, humid conditions are ideal for spore germination and the proliferation of bacteria and fungi.

Gaps. Field-based estimates of production losses due to weeds, insects and diseases with increasing carbon dioxide and/or climate change are lacking. Little information is available on how changes in carbon dioxide and/or temperature could alter weed populations, seed bank dynamics and species diversity of weeds. Although changes in climate and carbon dioxide could alter the efficacy of chemical, mechanical and biological pest control, the nature of these changes is unknown. Basic research on the comparative ecophysiology of crops and pests to carbon dioxide and/or climate change to determine range and distribution of troublesome pests is unavailable. Potential pest migrants should be identified, as well as new combinations of crops and pests. For insects and pathogens, indirect effects of carbon dioxide on the host plant that could alter resistance or tolerance (e.g., changes in the production of secondary compounds, changes in water content, nitrogen status) have not been well characterized. For all pests, multiple interactions between carbon dioxide and other key climatic variables (e.g., high temperature, drought, tropospheric ozone and UV-B radiation) that directly affect productivity are unavailable.

Goals

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

Approach

An interdisciplinary approach among molecular biologists, plant physiologists, entomologists, pathologists and computer modelers will be used to measure, predict, and assess the impacts of carbon dioxide and climate change on the susceptibility of agriculture to weeds, insects, and diseases. Because of the varied and diverse nature of the goals to be addressed, it is recommended that a variety of facilities be utilized in the approach.

Outcomes

- Verifiable, physiologically based criteria will be determined to assess and predict losses in economic yield induced by weeds, arthropod pests, and diseases with climate change.
- Improved crop management systems will be developed that minimize economic and environmental uncertainties while maximizing the positive aspects of global change in agriculture.

Impact

A sustainable crop production management system that maximizes productivity while minimizing pest damage under changing climate conditions

Linkage with other ARS National Programs

- Air Quality
- Arthropod Pests of Animals and Humans
- Crop Protection and Quarantine
- Integrated Agricultural Systems
- Plant Diseases
- Plant, Microbial, and Insect Germplasm, Conservation, and Development
- Rangeland, Pasture, and Forages

Action Plan:

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

Introduction

Background

The essential role of water in sustaining all forms of life--plant, animal, and human--and the enormous contribution of water to economic development throughout human history have been recognized for millennia. During the past century, major advances have been made in quantifying the primary components of the hydrologic cycle, i.e., the cycling of water between the atmosphere, the land, the oceans, lakes and streams, and groundwater. However, there is a consensus in the scientific community that our understanding of the fate and movement of water and sediment in agricultural landscapes and watersheds remains inadequate. The many societal problems that we face related to water availability, use, control, and management are not new. They are just bigger and more complicated because of global change, increasing populations, rising standards of living, and the many diverse and competing demands for the Earth's finite fresh water resources. To achieve optimal use of this vital resource under conditions of global change, scientifically based procedures are needed to assess the economic and environmental consequences of different water resource management strategies and policies at the farm, ranch, and regional river basin scales.

The National Research Council has conducted a number of major studies on the research challenges and opportunities in hydrology and on the critical future needs of water and watershed management strategies. Many of the identified major challenges in hydrology relate to the problems of quantifying the space-time variability of both weather and climate data and of landscape and watershed characteristics. While various global climatic models agree on trends and directions of average global temperature changes, there is little agreement on the frequency and distribution of precipitation on a regional scale. The agricultural sector is particularly sensitive to precipitation variability. Some progress, however, is being made in monthly and seasonal precipitation forecasts at the regional scale. To fully utilize these forecasts at the farm and ranch scale, precipitation variability must be quantified over shorter time scales and from the region to local scales. The natural variability of weather demands the development and long-term operation of intensively instrumented agricultural watersheds to establish reliable, long-term databases in several diverse geographical regions. This demand is predicated on the need to assess impacts of variable weather on agricultural activities.

Several recent reports and publications address what is considered to be the most critical emerging water problem of the 21st century, namely water scarcity. Some of the reports project that about 45 percent of the world's population could be affected by either water stress or water scarcity by the year 2050. The projected severity of the problem of water scarcity could lead to serious economic, political, and even military conflicts in many parts of the world. The competition for water in many western states is projected to have major impacts on agriculture. Water scarcity is further exacerbated by weather and climate variability. Several reports suggest that in a warmer environment, weather and climate will become more variable with greater occurrence of extreme events.

The major economic and environmental damages associated with extreme climatic events also must be considered in developing strategies and policies for managing agricultural watersheds in a changing environment. During the past decade, the average annual cost of the damage to property from floods alone is estimated to be in excess of $5 billion. The Federal Emergency Management Agency's records indicate that more than 50 percent of all the Presidential disaster declarations since 1965 were related to flood damage. Economic damages from the 1993 Midwest flood alone are estimated to have exceeded $16 billion. Droughts can be even more devastating to communities than floods. The drought of 1988 was the most costly natural disaster in U.S. history. The total cost of the economic losses from this one drought is estimated at more than $39 billion. Over the long term, climatic extremes and poor land management practices lead to desertification (land degradation). One sixth of the world's populations are threatened by the effects of desertification, and 76% of the drylands of North America are degraded.

Water conservation, water use efficiency, and watershed management play critical roles in the development of cost-effective solutions to social, economic, and environmental problems caused by water scarcity, water stress, and extreme climatic events. An improved understanding of the hydrologic processes that determine the fate and movement of water in agricultural watersheds is critical to the development of effective strategies for water management in a changing environment.

Reliable techniques need to be developed for quantifying water resource responses to climate- forcing and using that information to predict the hydrologic consequences of global change. This research thrust would require a major long-term commitment of resources to the monitoring of water and energy fluxes over a range of scales and to the development of accurate, cost effective methods to characterize watersheds and simulate their integrated responses at the regional river basin scale.

Vision

Abundant fresh, clean water resources for all

Mission

Develop management strategies for farm, ranch, rural community, and natural resource decision-makers to conserve, store, and allocate water resources to address the many diverse demands and impacts on the Nation's rural water resources caused by global change.

Table 5. ARS locations contributing to the Changes in Weather and the Water Cycle at Farm, Ranch, and Regional Scales Component of the Global Change National Program

Global Change National Program Component IV: Changes in Weather & the Water Cycle at Farm, Ranch, and Regional Scales							
State	**Locations**	**Interaction of Water & Energy Balances in Large Heterogeneous Agricultural Systems**	**Land Use & Land Cover**	**Changes in Water Availability**	**Climate & Weather Variability & Extremes**	**Changing Snowpack Accumulation & Seasonal Water Yield**	**Scaling of Climate Change to Field, Farm, Ranch, & Regional Scales**
AZ	Tucson	X	X	X	X		X
GA	Tifton			X	X		
CO	Ft. Collins	X	X	X	X		X
MD	Beltsville	X	X	X		X	X
ID	Boise	X	X	X	X	X	X
OH	Coshocton	X		X	X		
OK	El Reno	X	X	X	X		X
MS	Oxford			X			X
NM	Las Cruces				X	X	X
TX	Temple	X	X	X	X		

Interaction of Water and Energy Balances in Large Heterogeneous Agricultural Systems

Problem Statement

Rationale. Whether global change is the result of human activities or part of long -term cycles, agriculture must be able to monitor and model the processes in order to respond, plan, and predict. The key to much of climate research is understanding the hydrologic cycle at large scales. Shifts in the spatial and temporal distributions of water and energy can dramatically impact short-term climatic events and longer time scales, from seasonal and annual to longer cycles. Understanding the interaction of the land surface and atmospheric circulation is complex because of the high degree of variability in the land surface (as opposed to the oceans). Our understanding must be scaled to basin, regional, and ultimately global scales to project reliably the impact of climate changes on agricultural systems.

What is known. Complex patterns of the landscape with varying topography and surface features (i.e., vegetation and snow cover, soil moisture, surface temperature) strongly influence the function of hydrology and climate systems, and hence, these patterns need to be incorporated into land surface models. Techniques to integrate process information from farm to regional scales are being developed but are still conceptual. When fully developed, these aggregation techniques ultimately will lead to improved prediction of future climate change and resulting effects on agricultural systems. With increasingly reliable information, resource managers and farmers can make better agricultural decisions related to the frequency and timing of grazing, planting, and harvesting.

Gaps. We have had little success in applying complex water and energy balance models to large complex regions. This stems from the limited understanding of the linkage between atmospheric and hydrologic processes at specific points and averaged processes typical of the basin and regional scale. Concurrent with the need to represent scales without ignoring the processes, we need to develop models that integrate basin data of various types and at various scales. Providing input, calibration, and validation data to drive these models is a significant challenge.

Goals

- Utilize current and future satellite remote sensing systems and develop new technologies to measure landscape properties and agroecosystem health over a range of scales;
- Investigate the use of remote sensing to scale up surface properties that affect water and energy balances from local to regional scales; and
- Provide products and tools to resource managers, farmers, and ranchers that permit them to develop management strategies based on present and future climate conditions.

Approach

Remote sensing offers the most practical method of providing information over large geographical areas. Operational and research sensors are being developed that will create opportunities for new and innovative approaches to measuring components of the hydrologic cycle. Techniques will be developed to integrate remote sensing measurements and spatial analysis technologies such as geographic information systems (GIS) into land surface models. This will require the development of techniques to combine remote sensing data to estimate a variety of land surface characteristics. Work will focus on evaluating the utility of sensors on the recently launched National Aeronautical and Space Administration (NASA) Earth Observing System TERRA satellite. Data will be incorporated into a GIS that can, in turn, be integrated with models to compute spatially distributed evaporation rates and permit the estimation of evaporation and the surface energy balance at larger scales. Many of these experiments have been, and will continue to be, carried out in ARS Experimental Watersheds in a variety of hydro-climatic regions across the U.S.

Outcomes

- Procedures and techniques will be developed to estimate hydrologic and agricultural parameters from remotely sensed data.
- Methods to monitor water and energy fluxes at large scales will be more reliable.
- Environmentally stressed areas will be more detectable using remote sensing.
- Water management strategies will be more responsive to the effects of global change.

Impact

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

Linkages to Other ARS National Programs

- Water Quality and Management

Land Use and Land Cover

Problem Statement

Rationale. Human-induced changes that include changes in species and land use and land cover significantly impact local and regional water and energy balances. These changes can further impact land use and cover, potentially resulting in major impacts on U.S. agriculture and the environment.

What is known. Land use and land cover change due to increasing population and large-area application of agricultural practices is one of the largest single mechanisms of global change. Unprecedented global land conversion continues to occur with increasing needs for food, fiber, and homes. Climate change or changes in carbon dioxide also can significantly impact the transpiration and water-use efficiency of vegetation. In agricultural systems, this will be a factor in determining the vegetation that can be economically grown in a region. On range and forest lands, this often will create shifts in vegetation or encourage establishment of nonnative species. Whatever the reason, changes in land use and land cover are known to have significant impact on soil erosion and the transport of nutrients and pesticides threatening the long-term sustainability of these resources.

Gaps. At present, poor understanding and a lack of information regarding hydrological and biological processes across multiple scales hinder assessment of the ecological consequences of human actions. We need to develop accurate modeling techniques to incorporate land use and land cover data into hydrological and agroecological models across multiple scales. The widespread acceptance and use of remotely sensed data will continue to depend on the quality of the information it yields. However, mapping and species classification inaccuracies or errors can occur at many steps throughout any remote sensing project. Therefore, a detailed analysis needs to be developed to assess the effects of the accuracy of land cover estimation on model response. In addition, current models do not simulate vegetation succession and need refinement to quantify the effects of global change on water supply and crop production.

Goals

- Develop improved methods to determine individual plant species from satellite data;
- Develop models and prediction methodologies to assess vegetation succession under varying carbon dioxide, climate, and management scenarios; and
- Develop improved models to assess regional environmental and economic consequences of changes in land cover including water supply, water quality, and agricultural production.

Approach

New and/or improved methods are needed to determine specific plant species from satellite data to improve input for simulation models. Models must be improved to evaluate the impacts of land use and land cover changes on crop production, water supply vegetation succession, and environmental response. Techniques will be developed to automate parameters for the models using GIS data (e.g., land cover, topography, soils) because the vast majority of modern agricultural, hydrological, and ecological models require a large number of input parameters. The impacts of data resolution and remotely sensed land cover misclassification error on model response will be quantified. The degree of model complexity and the required accuracy for modeling and assessment at a range of scales will also be examined. Basic research will continue to fill knowledge gaps in the role of carbon dioxide and climate change in the invasion of certain vegetation species and on evapotranspiration, crop water use and irrigation needs, and water yields. NRCS, EPA, and NASA, among others, have clearly identified land use and land cover change as major agents of global change. Joint research with these agencies to assess the consequences of land use and land cover change is already underway at a number of ARS locations. Multiagency efforts addressing this problem area will continue.

Outcomes

- Improved data, models, and decision support systems will be developed to assess the effects of global change on vegetation response, environmental response, and economic returns.
- Management strategies will be developed to ameliorate the impacts of global change on agricultural and natural lands.

Impact

Sustainable agricultural systems for farm, range, and forest lands

Linkages to Other ARS National Programs

- Rangeland, Pasture, and Forages
- Soil Resource Management
- Water Quality and Management

Changes in Water Availability

Problem Statement

Rationale. The El Nino-Southern Oscillation (ENSO) strongly influences precipitation in parts of the U.S. If climate change disrupts the dynamics of this large-scale ocean-atmospheric phenomenon, water availability for human and natural resource needs could be affected. More variable precipitation patterns will impact streamflow, surface reservoirs, groundwater aquifers, and available soil water. These changes could increase the level of risk in agricultural production and water supply. Temperature changes could alter the loss of water from plant and soil surfaces (evapotranspiration), resulting in plant water stress and decreased production.

What is known. Droughts or periods of excess rainfall seriously affect agricultural production with resulting impacts on the U.S. economy. Changes in current weather patterns will substantially affect water availability.

Gaps. The impacts of global change on the temporal and spatial distribution of precipitation and resulting water availability are unknown. It is recognized that elevated atmospheric carbon dioxide affects plant water use, but the effect on regional crop water use and evapotranspiration is uncertain. The effects of global change on ENSO and related large-scale weather patterns and the resulting effects on water availability are unknown. Current weather generation and natural resource models can not quantify the effects of global change on water yield and water availability.

Goals

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

Approach

New and/or improved models will be developed to analyze the influence of changes in atmospheric carbon dioxide and other greenhouse gases on water and energy transfer controlling the interaction among climate, precipitation, plant water use, surface water movement, and streamflow. Precipitation models will be developed that express the influence of changes in ENSO and other weather processes on precipitation by regions and season. Model improvements will be accomplished by coupling additional field research with new modeling approaches. Data from ARS Experimental Watersheds and long-term precipitation records will be used to modify, develop, and validate the models. The models, coupled with global change forecasts and real-time or remotely sensed data, will be used to estimate the effects of global change on water supply and availability.

Outcome

Improved models, data bases, and other tools will be available to water resource managers for assessing the effects of global change on the availability of water for agricultural and domestic uses.

Impact

Improved management of the water supply for sustaining agricultural production while protecting the environment

Linkages to Other ARS National Programs

- Water Quality and Management

Climate and Weather Variability and Extremes

Problem Statement

Rationale. Extreme climate and weather events often cause extensive flooding and sustained droughts that profoundly impact our society in general and agriculture in particular. Agriculture is vulnerable to variations and fluctuations in weather and climate because existing agricultural practices were developed for average weather and climate conditions. Even relatively small but persistent changes in the climate could disrupt efforts to optimize yields and achieve stable and sustainable agricultural production. Water resource systems also are sensitive to variations in climate, as are conservation of soil and water; management of water quality, waterways, and irrigation systems; and restoration and preservation of natural habitats and ecosystems. In light of our current understanding of climate variability, we need systematically to evaluate and improve our ability to define, model, and predict impacts of variations in climate at spatial and temporal scales relevant to agriculture and water resource management.

What is known. Current utilization of weather information in agriculture is based on the traditional assumption that weather is an independent random variable and can be quantified by traditional statistical methods. Furthermore, past climate and weather-related disasters have been shown to be associated with extreme year-to-year variations in weather and climate. Our understanding of, and ability to predict, global atmospheric and oceanic circulations and their long-distance effects have significantly increased in the last decade. Both the daily weather and its integration into climatic values are now recognized as strongly influenced by regional- and global- scale phenomena, including long-term fluctuations in the global atmospheric-oceanic system. This new knowledge of the climate system enables National Oceanic and Atmospheric Administration (NOAA) to produce, with some success, seasonal climate forecasts up to a year in advance. These forecasts and our increased understanding of the physics of climate and weather are critically important for planning and managing agricultural and water resources, as well as for conservation of soil and water, operation of irrigation systems, and assessment of nutrient and pollutant movement.

Gaps. Agricultural-oriented probabilities of the occurrence of extreme events are scant, so there is little effective utilization of such information in many aspects of the planning, management, and mitigation processes. There also is a need to augment our data and knowledge of the spatial and temporal variability and distribution of weather and climate at all scales and to identify impacts on all components of the agricultural system. Current weather generation models used in agricultural applications are limited in reproducing fluctuations in weather or responses to global climate phenomena such as El Nino. NOAA's probabilistic seasonal climate forecasts require evaluation, analysis, development, and implementation for use in agricultural and natural resource management.

Goals

- Develop quantitative characterizations of variability and extremes in climate and weather at day-to-decade and farm-to-regional scales;
- Predict agricultural productivity and conservation impacts and watershed response under variable and extreme climate and weather conditions and develop production, management, and mitigation alternatives for such conditions;
- Identify and assess ways in which producers and agribusiness might use climate forecasts and develop interface tools that enhance the value of the forecasts;
- Incorporate NOAA's seasonal climate forecasts into risk-based decision, management, and conservation tools and identify related agro-climatic parameters and corresponding risk for use in conjunction with the forecasts to identify and quantify the impact of forecast climate conditions on agricultural production; and
- Improve weather generation models to reflect fine-scale fluctuations and extremes associated with global-scale atmospheric phenomena.

Approach

The characteristics of variability and extremes in climate and weather can be identified and quantified by applying statistical techniques and spatial analysis to long-term series of climatic records. These analyses would then be correlated with known indices describing atmospheric circulation, ocean temperature, and other global phenomena. NOAA's seasonal climate forecasts should be evaluated to determine their reliability, information content, and application potential for agricultural planning and management needs. Transformations of the forecast climate and probabilities could then be developed for agricultural applications. Weather generation capabilities at all time scales should be improved by incorporating emerging understanding of spatial and temporal variability relationships, radar and other remotely sensed weather information, as well as correlation with global phenomena. The impact of climate and weather variability and extremes on agricultural productivity, conservation, and environmental quality can then be assessed by application of models and evaluation of historical data from the ARS network of watersheds.

Outcomes

- NOAA's seasonal climate forecasts will be used effectively in agricultural planning and management, as well as in soil and water conservation efforts, to reduce risk, stabilize production, and increase profits.
- Integrated information systems will be available to interpret, quantify, and apply climate forecasts for risk-based use by agribusiness and environmental managers.
- The impact of long-term climate and weather fluctuations on agriculture and resource conservation will be established.
- Flexible production strategies and mitigation alternatives will be used to adapt to and benefit from opportunities arising from climate variations.
- Improved weather generation models will provide a broader and more representative range of weather conditions for use in agricultural, watershed, and process models.

Impact

More sustainable and profitable agricultural systems informed by climate and weather variation and forecasts

Linkages to Other ARS National Programs

- Crop Production
- Food Animal Production
- Integrated Agricultural Systems
- Rangeland, Pasture, and Forages
- Soil Resource Management
- Water Quality and Management

Changing Snowpack Accumulation and Seasonal Water Yield

Problem Statement

Rationale. Snow is a major source of water for agriculture and water supply in some parts of this country and a potential cause of flooding in others. In the western U.S., irrigation depends heavily on an adequate snowmelt season, and a major irrigation water distribution infrastructure has developed since the mid-1800s. If climate change affects the accumulation of snow and the manner in which the snowpack melts, irrigation management practices developed over a century-and-a-half and irrigation structures in place for many years are in jeopardy. Irrigation water managers and farmers need reliable projections of changes in snow water supplies for the 21st century.

What is known. Water supplies for irrigation, hydropower, domestic consumption, and recreation are already over-committed in the western U.S. because of ever-increasing water demands. If the current climate projections through the 21st century are realized, it is likely that both snowpack accumulation and melt will be diminished, further increasing the gap between water demand and water supply. Accurate assessment of snowpack water volume and forecasts of snowmelt runoff increase the ability of water managers and farmers to make realistic decisions about what crops to plant and when to irrigate.

Gaps. Inadequate ground-based observation networks do not allow accurate assessment of areal snow water equivalent in mountain or lower elevation basins, thus causing significant uncertainties about the snow water volume stored for spring melt. We therefore need better methods to assess snowpack. Snowmelt runoff models for forecasting generally do not use areal data provided by new methods. Few distributed snowmelt runoff models are available that can produce complete daily hydrographs for the entire snowmelt season. Even fewer snowmelt runoff models are noncalibrated and suitable for use in future climate change regimes.

Goals

- Develop methods for areal snowpack assessment that integrate different remote sensing data types and conventional techniques;
- Develop noncalibrated, distributed snowmelt runoff models that use remote sensing data and can be used with future climate change inputs; and
- Provide tools to water managers and farmers that enable them to develop climate change strategies for the future.

Approach

New snow cover mapping approaches will be developed using high resolution techniques and satellite data. Snow water volume will be measured using the improved resolution satellite microwave sensors. Techniques to project snow cover depletion in future climates will be developed depending on snow water equivalent, temperature, radiation, and precipitation scenarios. Snowmelt models of differing complexities will be developed for use by decision- makers and managers. Selection of models for use in developing hydrologic scenarios of the future will depend on user application and data availability. Several basins will be selected to illustrate the performance of the different models in each decade of the 21st century. Selected NRCS locations will be used to test the resulting models.

Outcomes

- Measurement of snow cover extent and snowpack water equivalent in mountains will be improved, as will snowmelt runoff forecasts.
- Methodology for creating future hydrologic scenarios under conditions of climate change will be developed allowing users to create their specific scenarios depending on their end objectives (e.g., irrigation planning, hydropower).
- Decisions on future crops and irrigation strategies and plans for updating irrigation control structures will be improved through modeling scenarios.

Impact

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

Linkages to Other ARS National Programs

- Crop Production
- Food Animal Production
- Integrated Agricultural Systems
- Rangeland, Pasture, and Forages
- Soil Resource Management
- Water Quality and Management

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

Problem Statement

Rationale. Complex terrain and variable elevations have strong, nonlinear effects on precipitation amounts and form. These factors have a major impact on snow distribution, which drives agriculture through irrigation and, in the Pacific Northwest, power generation and biomass production of animal forage and timber, both economically critical to the region. It is not clear how average annual climate change estimates for the region should be distributed on the landscape and what effect those changes will have on snow hydrology and biomass production.

What is known. Spatial variability in range biomass and rainfed cropping systems can be tremendous because of natural variability in the landscape topography, soils, and associated water movement. Hydrologic processes, such and infiltration and surface runoff, are known to depend upon the size of the domain of study and process interactions at smaller scales. The distribution of plant communities and plant biomass production are strongly influenced by topography and elevation, and these are largely driven by topographic effects on the climate. Within relatively short distances (a few miles) one can observe several-fold increases in biomass and runoff production. These effects are not linear. The distribution of snow is highly nonuniform both in space and time. Average regional climatic change impacts on the processes of snow accumulation and melt probably will not be distributed uniformly in space.

Gaps. Sustainable agricultural management and prediction of agricultural production and environmental changes at relevant management scales require an understanding of the causes of hydroclimatic processes affecting plant growth from plot to watershed scales. Rigorous prediction of the scaling behavior is lacking. We do not have modeling systems capable of accurately integrating plant water use and biomass production at a management scale (e.g., ranch) in such spatially heterogeneous environments. We do not know how to distribute the impacts of a spatially average projected climate or vegetation change over complex terrain.

Goals

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

Approach

Soil hydraulic properties and water contents will be measured at high resolution on an operational dryland cropping field and rangeland pastures with significant topographic undulation. Measured rainfall along a transect will be used to simulate numerically water movement by both overland and subsurface (predominantly unsaturated) flow, and simulated water contents will be compared with observed soil water contents, thereby disaggregating and identifying dominant processes. The space-time variability of soil water will be determined from these measurements and process-based simulations. Spatially measured biomass and yield will be related to water patterns, soils, and topographic attributes. Field and remote sensing measurements will be made at different scales and altitudes and used to develop simulation models that incorporate topographically-induced spatial heterogeneity. Aircraft observations are critical for scaling activities because they provide a common meeting point at the landscape level for the scaling up of ground-based plot studies and the scaling down of regional satellite coverage. Finally, we will use collected field data to test and validate our soil freezing models and use measured streamflow and aerial photography to test and validate the snowmelt models.

Outcomes

- Scaling of space-time soil-water patterns from landscape information and derived attributes will be possible over a range of scales for estimation of crop and rangeland productivity.
- A model that can be operated at management scales will be developed and tested.
- A series of hydrologic models and verification data sets will allow us to describe the effects of climate on runoff.
- Environmental fluxes and biomass production will be predictable over a range of spatial and temporal scales using limited soil and water data.
- The model will be incorporated into different applications that facilitate use in a decision support model for different range management and global change scenarios.
- Tools will be developed to test the potential impacts of global change and management decisions on cold season runoff processes.

Impact

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

Linkages to Other ARS National Programs

- Crop Production
- Food Animal Production
- Integrated Agricultural Systems
- Rangeland, Pasture, and Forages
- Soil Resource Management
- Water Quality and Management

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