Carbon Cycle Science
Abstracts of selected proposals.
(NNH10ZDA001N-CARBON)

The National Aeronautics and Space Administration (NASA) solicited proposals to conduct carbon cycle research within the NASA Earth Science Program, the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) Agriculture and Food Research Initiative Competitive Grants Program (AFRI), and the USDA Forest Service Program (working through the USDA-NIFA-AFRI program). NASA and USDA-NIFA carbon cycle research contributes toward the goals of the USGCRP and the U.S. Ocean Action Plan by providing critical scientific information about the movement of carbon in the environment and potential near- and long-term changes in the carbon cycle, including the role of and implications for societal actions. U.S. carbon cycle research addresses two broad questions:

- How large and variable are the dynamic reservoirs and fluxes of carbon within the Earth system and how might carbon cycling change and be managed in future years, decades, and centuries?
- What are our options for managing carbon sources and sinks to achieve an appropriate balance of risk, cost, and benefit to society?

In this solicitation, NASA and USDA-NIFA requested proposals for research and/or applied science investigations to address these questions in a manner that is responsive to the National Research Council's call for "research on the end-to-end climate change problem, from understanding causes and processes to supporting actions needed to cope with impending societal problems of climate change." Proposals within five research themes were requested. Each agency participating in this solicitation will be able to support research only in a subset of these themes, and the participating agencies are noted in parentheses for each theme listed below. The five research themes are:

1. Interactions between land management and land change and the carbon cycle (NASA, USDA);
2. Ocean acidification (NASA);
3. Advancing the scientific basis for space-based measurements of atmospheric carbon dioxide and/or methane (NASA);
4. Adaptation, mitigation, and vulnerability within the Earth system (land, ocean, and atmosphere) (NASA, USDA); and
5. Synthetic and integrative research to advance the carbon-related goals of ongoing research activities under the U.S. Carbon Cycle Science Program and the carbon-related goals and objectives of related national and international programs. (NASA, USDA).

A total of 139 proposals was received, and 34 have been selected for funding. The total funding to be provided for these investigations is approximately $26.1 million over three years. The investigations selected are listed below. The Principal Investigator, institution, funding agency, investigation title, and proposal summary are provided. Co-investigators are not listed here.

Wolfgang Buermann/Institute of the Environment, UCLA/NASA Funded Detection and Attribution of Rapid Large-Scale Shifts in the Terrestrial Carbon Cycle

A series of recent studies have suggested that the Earth underwent significant synchronous climatic shifts around 1988/89 towards enhanced warming in the northern latitudes and increased solar radiation associated with reduced cloudiness in the tropics. A new synthesis analysis based on the growth rate of atmospheric CO_2, fossil fuel emission estimates, and modeled ocean CO_2 uptake reveals that there may have been also a major shift towards greater land carbon uptake around this time frame. The detection and attribution of rapid large-scale shifts in the global carbon cycle is of primary concern for society since they lead to feedbacks that either amplify or diminish physical climate change.

The overall goal of this proposal is, therefore, to develop a general framework for the detection and attribution of rapid regime or large-scale shifts in the terrestrial carbon cycle. The framework consists of statistical methods to detect changes in the fundamental behavior of the carbon cycle as well as terrestrial ecosystem modeling components to unravel the processes that are responsible for these shifts.

In order to achieve these goals, we propose to do the following:

1) Develop a capability for detecting and attributing temporal shifts in the terrestrial carbon cycle. We will apply statistical methods such as change point analysis on key time series in the context of the carbon cycle. The time series include inferred net land uptake from ocean and atmospheric studies, as well as key observational climate and satellite vegetation data sets. The aim is to identify coherent signals in a broad range of observation and synthesis data sets.

2) Perform global simulations with an improved version of the terrestrial biogeochemical model CASA driven with a consistent satellite-derived FPAR data set for the period 1982-2009/10 and climate forcings. The aim is to independently identify regions/ecosystems in which carbon uptake is consistent with the timing, magnitude and spatial distributions of carbon sinks derived from atmospheric and oceanic studies (Objective 1).

3) Identify the fundamental biological, physical, and anthropogenic mechanisms responsible for the rapid shift in carbon uptake derived from atmosphere and ocean studies (Objective 1) with a focus on the regions identified in Objective 2. We will consider the impacts of climate forcings, land use change, fires, and CO2 fertilization on land-atmosphere CO_2 fluxes. To clearly isolate the roles and assess the robustness of individual mechanisms, we will perform a set of simulations with two ecosystem models (CASA and Ed2) of varying degree of complexity and observational constraints.

This project directly addresses one of the central themes in the NASA carbon cycle science: 'How large and variable are the dynamic reservoirs and fluxes of carbon within

the Earth system?'. Inasmuch as one of our main emphases is on identifying mechanisms of the variability in sources and sinks, our project also addresses the priority topic 'How might carbon cycling change and be managed in future years, decades, and centuries?'. The possibility of large-scale carbon cycle feedbacks operating on short times scales is a key concern for society due to its high impact on the trajectory of physical climate change.

Amy Burgin/Wright State University/USDA Funded
Conversion of Farm Fields To Wetlands: How Do Created Wetlands Affect Global Warming Potential?

Wetlands provide many ecosystem services, including water quality improvement and habitat for rare species. However, the net greenhouse gas emission from wetlands is uncertain. US governmental agencies have established policies to protect and increase the numbers of wetlands. Created wetlands, however, are criticized for not being functionally equivalent to natural wetlands. Simultaneously, the US government has established directives to mitigate atmospheric carbon dioxide increases by sequestration in terrestrial ecosystems; wetlands are well-established stores of carbon. This makes it imperative to understand the interaction between policies aimed at both wetland restoration and climate mitigation. Therefore, we ask: Is restoring agricultural lands to wetlands synergistic or antagonistic with the goals of climate change mitigation?

Our challenge is to understand how the construction of wetlands from former aglands affects greenhouse gas flux and carbon storage. To do so, we will test the overarching hypothesis that wetland creation on former agricultural lands will alter the site's global warming potential due to: 1) the construction activities associated with wetland creation, and 2) the biogeochemical contrast between drained and submerged soils. Testing the more specific hypotheses underpinning this broad hypothesis will lead to a mechanistic understanding how soil physics, microbiology and management interact to affect the net global warming potential of a created wetland over both the short and long-term transition from an agricultural field.

This project takes advantage of the initial phases of construction of a wetland in southwest Ohio, a project undertaken and financed by the stakeholder and ecosystem management group, Five Rivers Metro Parks (FRMP). To test our hypotheses, we will measure methane, nitrous oxide and carbon dioxide fluxes as well as carbon storage (the balance between plant growth and decomposition) pre- and post-wetland construction. The balance between these emitting and sequestering processes underpins our knowledge of how biogeochemical services operate in created wetlands, and thus if created wetlands will attain the same carbon storage capacity as natural wetlands. Understanding both the timing and mechanisms of emitting and sequestration processes are critical to predicting if a wetland will be a net greenhouse gas source or sink.

Our interdisciplinary research will yield a mechanistic framework to understand the how the understudied short-term transition from agland to wetland alters greenhouse gas fluxes and carbon storage. As land managers attempt to scale increased numbers of

restored wetlands, this information will be critical to reducing the large uncertainty around existing measurements. Our research question directly addresses the themes of "interactions between land management and land change and the carbon cycle" (#1) and "adaption, mitigation, and vulnerability within the Earth system" (#4). This project also meets to the NRC's call for "research on the end-to-end climate change problem" by engaging a resource management group (FRMP) to leverage their wetland restoration project to "strengthen research on adaptation, mitigation and vulnerability."

Eric Davidson/The Woods Hole Research Center/NASA Funded
Linking High-Frequency, Automated Measurements of Greenhouse Gas Emissions From Soils With Microwave-Based Estimates of Soil Saturation in Agricultural and Forest Landscapes

Soils are important sources and sinks of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Soil moisture can change rapidly, and it is one of the dominant factors controlling soil aeration, and hence the balance between aerobic (CO_2 producing) and anaerobic (CH_4 producing) microbial respiration. Production and consumption of N_2O are also highly dependent on spatial and temporal variation in soil moisture. However, studies of soil fluxes of CH_4 and N_2O at high temporal frequency have been hampered by lack of appropriate technology for in situ real-time measurements. Flux estimates are subject to large errors when temporal variations are inadequately sampled. Opportunities for mitigation to reduce greenhouse gas emissions could be missed due to lack of understanding of transient spikes in emissions in response to rapidly changing environmental conditions across agricultural and forest landscapes. The proposal responds to research theme #1 “Interactions between land management and land change and the carbon cycle” and is also relevant to mitigation aspects of theme #4.

New satellite technologies are arriving to estimate soil moisture, a key driver of soil emissions of CO_2, N_2O and CH_4. The operational Advanced Land Observing Satellite (ALOS) and anticipated Soil Moisture Active Passive (SMAP) mission and Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) mission all feature microwave instrumentation with this capability. We propose to couple trace gas flux measurements to estimates of seasonal and interannual variation of soil moisture and the area of saturated soils using L-band radar of the ALOS satellite. Our study sites in North Dakota include a commercial-scale agricultural experimental site and a mosaic of upland agriculture that drains to prairie glacial wetlands. Similarly, the Howland Forest, located in a region of actively managed forests of central Maine, includes soils ranging from well drained to very poorly drained over relatively small areas. Hence, the daily, seasonal and interannual variation of soil moisture and of area of saturated soils will likely affect landscape-scale fluxes of CO_2, N_2O and CH_4 in these agricultural and forest systems.

The advent of new cavity ring-down spectroscopy is about to transform soil greenhouse gas flux measurement methodology. Here we describe how an existing automated system that measures soil CO_2 efflux at half-hourly intervals can be integrated with new instruments to produce simultaneous measurements of soil CO_2, N_2O, and CH_4 fluxes. Given the exceptional stability, sensitivity, and fast response times of the new generation

of instruments for detecting changes in N_2O and CH_4 concentrations, we anticipate not only greatly increasing the frequency of measurements through automation, but also improving sensitivity and reducing uncertainty in flux measurements.

The objective of this project is to demonstrate how a combination of nested high and low temporal resolution field measurements of trace gas fluxes and soil moisture can be integrated with soil models and with remotely sensed L-band microwave data for a range of temporal and spatial scales. We will explore the biases and uncertainties of model simulations based on “snapshots” of radar-based soil moisture estimates at spatial scales from 15m (ALOS) to aggregations of ALOS data at 3000m resolution to simulate a SMAP pixel. Using hourly automated chambers at intensively studied sites and a temporally and spatially clustered design of manual measurements across a 3-km landscape, we will compare the temporal variation in measured and simulated fluxes and soil moisture contents to those likely to be captured by future SMAP and DESDynI estimates of soil moisture used to drive soil models. This type of analysis is made possible only by combining new technological developments in both flux measurements on the ground and remote sensing opportunities.

Kenneth Davis/The Pennsylvania State University/NASA Funded
Regional Atmospheric Inversions to Determine Land-Atmosphere Carbon Fluxes in the Southeastern Forests of the United States

Terrestrial ecosystems are buffering human-induced climate change by absorbing about one fourth of the carbon dioxide (CO_2) emitted into the atmosphere by fossil fuel burning. This terrestrial storage of CO_2, however, is difficult to measure. Quantification of these fluxes is essential to guide land management and climate change mitigation efforts. Atmospheric budgets, known as "inversions," provide one important means of quantifying forest carbon storage. At present, however, regional atmospheric budgets have limited accuracy and precision due to incomplete knowledge of atmospheric transport, and a limited number of high-quality measurements of the atmospheric concentration of CO_2.

The first component of this study will use data from the North American Carbon Program Midcontinent Intensive (MCI) regional experiment, which took place in the upper Midwest of the US from 2007-2009. We will use data from this experiment to evaluate, quantify, and reduce the impact of uncertainty in atmospheric transport on our ability to make inverse flux estimates. To do this we will run many different versions of a widely tested atmospheric transport model to simulate atmospheric winds and CO_2 concentrations in the MCI region. Each model version will represent a plausible realization of atmospheric conditions. We will then compare the multiple model results to a suite of regional measurements of atmospheric properties and CO_2 concentrations to identify more and less realistic versions of the model, and to quantify the range of uncertainty that remains among the plausible model versions.

We will then use this knowledge to improve our estimates of the CO_2 balance of the upper Midwest. The uncertainty in these flux estimates will be more realistic and smaller

than past estimates. Further, we will use our model results to evaluate how much space-based measurements of the column density of CO_2, as will be obtained from the Orbiting Carbon Observatory-2 (OCO-2), would improve our regional CO_2 flux estimates.

The second stage of this study will apply these methods to derive greatly improved estimates of CO_2 and methane (CH_4) fluxes from the Gulf Coast region of the southeastern (SE) US. The forests of the southeastern United States are highly productive, heavily managed, and susceptible to climate change. These forests represent a dynamic element of the carbon budget of the United States. Atmospheric inverse studies and terrestrial carbon cycle models, however, do not yield consistent findings regarding land-atmosphere fluxes of carbon in this region.

We will deploy the "ring of towers" technology that we demonstrated in the NACP MCI regional study to these SE US forests. Each of 5 towers in the SE US will measure CO_2 and CH4 concentrations, and will complement 6 tower-based measurements that already exist in the region. These measurements will be deployed to coincide with the launch of OCO-2. Data from both tower and satellite will be combined with satellite-based measurements CH_4 from a second satellite sensor, the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY - used to measure atmospheric CH_4) to estimate the forest-atmosphere fluxes of CO_2 and CH_4 from the southeastern, Gulf coast states. Our improved understanding of atmospheric transport will be utilized to improve these estimates. We will then compare our results to independent estimates obtained from biomass inventories and biogeochemical models to see if these estimates converge. Discussions with regional forest and greenhouse gas managers and policy makers will be held throughout the project to determine their needs and the ability of our developing methodology to meet their needs.

The data obtained and methods developed during this project will be archived at DOE and NASA funded data centers to ensure that they are available to inform future studies.

David Glover/Woods Hole Oceanographic Institution/NASA Funded
Assessing the Impact of Ocean Acidification on Marine Planktonic Calcification Using Satellite Anlaysis and Earth System Modeling

Marine planktonic calcifiers such as coccolithophores, foramanifera, and pteropods play a fundamental role in the ocean carbon system, a role that may be modified substantially by rising atmospheric CO_2 and climate change. The overall goal of this project is to better constrain the magnitude of ocean acidification and climate change impacts on marine inorganic carbon dynamics, ocean carbon storage and atmospheric CO_2 levels over the next several decades to centuries. Our primary numerical tool will be the new Community Earth System Model, version 1 (CESM, v.1), a variant of the widely used Community Climate System Model (CCSM) that includes fully interactive marine ecosystem and global carbon modules. Satellite observations will be integral to the project in terms of both model parameterization development and model-data evaluation. The specific objectives are four fold:

1). Utilize historical satellite remote sensing (SeaWiFS; MODIS) and in situ data to characterize the biogeographic niche for marine calcifiers; i.e., the temperature, circulation and seawater chemistry "phase-space" for calcifiers;

2). Improve the existing CESM marine ecosystem module to incorporate more explicit ecological treatment of distinct biological calcifiers and modify biological calcification and carbonate dissolution rates so that they are sensitive to changing seawater chemistry;

3). Verify against satellite and in situ data the simulated fields of marine planktonic calcification including the spatial distributions and seasonal to decadal temporal variability;

4). Quantify the projected changes over the 21st century in the patterns and strength of marine biological calcification in a warmer, higher-CO_2 world and the resulting feedbacks on ocean carbon storage.

Samuel Goward/University of Maryland/NASA Funded
US Forest Disturbance History from Landsat

This proposal seeks to continue an effort that exploits the combination of two key data sets, the Landsat historical record and plot records from the US Forest Service (USFS) Forest Inventory and Analysis (FIA) program, for the purpose of developing a quantitative understanding of forest disturbance patterns in North America. The primary goals of this study are to: 1) Wall-to-Wall Annual Assessment of US Forest Disturbance History between 1985 and 2010. This approach not only reduces the errors encountered in early sampling efforts but also test automation of processing and analysis procedures which have previously been carried out in a handcrafted fashion. 2) The products of this comprehensive analysis, maps and statistics, will be subjected to a rigorous validation to provide quantitative assessments of the accuracy of these products. This will support interested users in understanding reliability our analysis. 3) An investigation of the satellite-observed forest recovery trajectories will be carried out in comparison to USFS Forest Inventory Analysis measurement. This work supports extended use of forest disturbance history analysis by linking the observed forest recovery with field measured growth dynamics. 4) The team will evaluate various attributes of the disturbance analyses, including the recovery trajectories and spatial patterns of the disturbed forest areas, to evaluate how successfully the causal factors that led to the observed disturbances may be extracted from the Landsat observations.

The proposing North American Forest Dynamics (NAFD) project team from the University of Maryland, USFS, and NASA has been working to accomplish this science goal as a contribution to the North American Carbon Program since 2003, when the team first began to explore whether Landsat time series stacks (LTSS) could be combined with FIA data for this purpose. In earlier phases of this work a national sampling approach has been used, mostly because of data cost and processing complexity. In this study we will transform our previous data processing and analysis to a more highly automated approach, exploiting the newly developed NASA Ames Research Center NEX computing

environment. Whereas in previous efforts we have examined no more that 2000 Landsat scene, in this study we will process and analyze over 15,000 scenes to produce this annual, nationwide assessment of forest disturbance history

The results from this study will not only be published in the scientific literature but a set of national map products, including annual disturbance history, national variations in forest recovery trajectories and nationwide analysis of the spati0-temporal patterns of underlying forest disturbance causal factors will be made available to interested users. This information is for vital importance to understanding the carbon balance of the US and the North American continent. North American forests are thought to be a long-term sink for atmospheric carbon, with much of the sink attributed to either forest regrowth from past agricultural clearing or to woody encroachment. However, the magnitude of the North American forest sink is uncertain, because disturbance and regrowth dynamics are not well characterized or understood. Disturbance events (including harvest, fire, insect and storm damage, and disease) strongly affect carbon dynamics in many ways, including biomass removal, emissions from decaying biomass, and changes in productivity. This proposed research should help reduce these uncertainties through integration of forest inventory data and satellite data. In addition, our approach of automating the processing and analysis steps in this study will serve as a necessary precursor to the implementation of operational national carbon monitoring system and the development of more aggressive systematic land survey missions.

Kevin Gurney/Purdue University/NASA Funded
A Global High-Resolution Fossil Fuel CO_2 Inventory Built From Assimilation of In Situ and Remotely-Sensed Datasets to Advance Satellite Greenhouse Gas Decision Support Systems

In order for atmospheric CO_2 observing systems (remote or in situ) to isolate the anthropogenic component of carbon flux at the surface, a space- and time-resolved estimate of fossil fuel CO_2 emissions is required. Whether combined with atmospheric transport in inverse/assimilation systems or used directly to infer sources, space/time resolved emission inventories provide five key elements to a greenhouse gas observing and decision-support system 1) an evaluation opportunity for satellite CO_2 measurements (particularly in the case of large surface sources) 2) a global high-resolution flux prior for inverse/assimilation systems optimizing the complete carbon budget 3) support for multi-tiered CO_2 observing system simulation experiments (OSSEs) 4) a step towards an independent verification system for national anthropogenic emission estimates and 5) decision support for emissions mitigation efforts executed at local scales.
The proposed research aims to build such a high-resolution global fossil fuel CO_2 inventory by processing several well-established datasets in the first application of an emissions assimilation system for fossil fuel CO_2. We will utilize national fossil fuel CO_2 emissions inventories downscaled in space and time through an optimal combination of Nightlights, Landscan population, MODIS temperature, urban extent, impervious surface, and SCHIAMACHY NO2 datasets, to name a few. These datasets will be used to constrain different components of a space- and time-varying, decomposed functional representation of energy consumption. Furthermore, the functioning of this new

emissions assimilation system will be tested by comparing the estimated inventories over high-resolution regional inventory efforts (eg. the “Vulcan” inventory - a NASA data product - over the U.S.).

The proposed research responds to area 3.3 of the NASA ROSES Carbon Cycle call and emphasizes both “Validation of satellite data products” and “Research to establish a stronger scientific foundation for future greenhouse gas monitoring systems or decision support capabilities utilizing satellite observations”. The construction of a global high-resolution fossil fuel CO_2 inventory will allow for calibration of satellite/transport inversion algorithms at a large number of large, well-constrained urban emissions “domes”. Future multi-tiered greenhouse gas monitoring systems, particularly those utilizing remotely sensed CO_2, will resolve smaller footprints. However, prior sub-footprint spatial structure is essential when optimizing fluxes with inverse approaches and simultaneously offers evaluation of international emissions reporting. Furthermore, mitigation options and decisions are most efficiently made at the scale of individual power plants, neighborhoods, and road segments: hence, a decision support system for mitigating CO_2 emissions and evaluating mitigation actions must attempt to resolve these spatial scales.

The new fossil fuel CO_2 emissions data product will be drive a global, mesoscale atmospheric transport model and time-dependent 3D CO_2 realizations will be generated. The transport realization of the fossil fuel CO_2 fluxes will not only offer evaluation opportunities for remotely-sensed CO_2 (via comparison to urban dome sources or other high-gradient CO_2 observations from GOSAT), but the complete time-dependent 3D fossil CO_2 concentration fields will assist in designing other components of a multi-tiered greenhouse gas observing system by guiding optimal observing network design.

A global inventory provides a key element in facilitating interaction between the scientific community and carbon information stakeholders (eg. policymakers & synthesis organizations). In order to maximize stakeholder interaction, we will build a web-based data retrieval and visual-analytics information system to deliver: hierarchical fossil fuel CO_2 emissions, all driver datasets, 3D time-dependent CO_2 concentration fields and interactive visualizations.

Sean Healey/United States Forest Service/NASA Funded
Installation of A Carbon Monitoring and Management Support Tool For The National Forest System

The U.S. Forest Service National Forest System (NFS) manages approximately one fifth of the country’s forestlands. NFS has been directed to more closely monitor the influence of forest management on forest carbon sequestration so that greenhouse gas mitigation may be incorporated into the forest planning process. While significant advances have occurred in the field of terrestrial carbon cycle modeling, many current approaches are insufficient for NFS’s needs because they: 1) may not extend beyond the ecosystem to capture cross-sector dynamics such as management-related fossil fuel emissions and storage of carbon in forest products; 2) may not support assessment at the sub-regional and local scales where most forest planning occurs; and 3) may not offer robust tracking of uncertainty. A system addressing these needs, called the Forest Carbon Management Framework (ForCaMF), has been developed through a partnership

between the Forest Service and NASA, and has been piloted in a county in Montana. Landsat imagery is critical to how ForCaMF visualizes the distribution of both forest carbon stocks and stock-resetting disturbances (e.g., harvests and fires) across individual planning units. Landsat-based change maps also contribute to the measurement of management-related emissions by quantifying forest road construction activity and pinpointing how far harvested timber must be hauled to move it from the forest to the mill. ForCaMF integrates monitoring of both ecological and non-ecological forest carbon dynamics under a probabilistic estimation framework, allowing annual assessment of carbon stocks and fluxes as they respond to particular harvest strategies and natural disturbance trends.

This proposal details a plan to install ForCaMF across 10 million hectares in the Northern Rockies as a template for broader integration into the NFS planning process. ForCaMF has the capacity to substitute user-generated hypothetical disturbance scenarios for remotely sensed histories of harvest and natural events. The resulting ability to compare the carbon effects of alternative scenarios is critical for establishing the net carbon benefit of one management approach over another. NFS recognizes ForCaMF's potential to transparently document likely carbon outcomes and uncertainties related to particular management strategies, and the Forest Service would pay more than 50% of the costs associated with this project. The proposed activities will not only likely lead to fundamental new insight into the relationship between forest management and forest ecology, but they will also improve the ability of the nation's largest forest manager to incorporate greenhouse gas mitigation into forest management planning.

Douglass Jacobs/Purdue University/USDA Funded
Forecasting Carbon Storage of Eastern Forests: Can American Chestnut Restoration Improve Storage Potential In An Uncertain Future?

Eastern deciduous forests represent an important proportion of the nation's forest carbon (C) stores, and imminent, largely anthropogenic forest changes present unique challenges and opportunities for this important C pool. A legacy of direct and indirect human impacts have altered tree species composition of eastern deciduous forests at regional scales, and this trend is likely to continue as new exotic pests spread throughout the forest. For example, fire suppression, gypsy moth, and forest management practices have begun a regional-scale replacement of oaks (Quercus spp.) by red maple (Acer rubrum), a species with low wood density and rapid decay, and it is not known how this will affect C sequestration and storage. Other potential pest-induced losses of ash (Fraxinus spp.), hemlock (Tsuga canadensis) and beech (Fagus grandifolia) may dramatically alter C storage in eastern forests. Such changes may affect short-term C biogeochemistry, long-term C storage capacity, and the resilience of these forests to new pests and climate change. However, the imminent reintroduction of blight-resistant American chestnut (Castanea dentata) has potential to increase C storage and ameliorate declines in other tree genera because of its relative shade tolerance, rapid growth rate, large size, longevity, and decay resistance.
We have assembled an interdisciplinary team of landscape modelers, statisticians, C scientists, foresters, and ecologists, and propose to forecast landscape scale C storage in

eastern forests under a set of plausible alternative futures that include expected and potential declines in existing tree species due to exotic pests, forest restoration activities targeting chestnut and oaks, and the direct and indirect effects of climate change. We will generate forecasts using a landscape disturbance and succession model (LANDIS II) with input parameters informed by targeted field studies, our recent remote sensing research, and an ecosystem physiology model (PnET-II). A factorial simulation experiment will test the effect of five factors (prescribed fire, climate change, existing insect pests, potential insect pests, and chestnut restoration) on C storage in eastern forests. By integrating our complementary research programs, we will be able to project the potential impacts of critical threats to future carbon storage and to evaluate the feasibility of a promising mitigation approach that would have been unimaginable merely a decade ago. Our research addresses Theme 1: Interactions between land use, land change and the carbon cycle and Theme 4: Research on adaptation, mitigation, and/or vulnerability to climate change.

Joanna Joiner/NASA Goddard Space Flight Center/NASA Funded
Reducing Carbon Flux and Transport Uncertainty In Inversion Models and Assimilation Through Improved Sampling and Precision of CO_2 and CH_4 Retrievals

Global satellite information about CO_2 and CH_4 concentrations are used to constrain source emissions and sinks in models. Thus far, CO_2 and CH_4 retrievals from space-based near-infrared solar backscatter measurements, such as from the Japanese Greenhouse gases Observing SATellite (GOSAT), have focused on cloud-free pixels. The accuracy and precision of these retrievals has been limited in part by the inability to detect small amounts of cloud and appropriately correct for aerosol contamination that affects nearly all such observations. In addition, the number of GOSAT pixels meeting the cloud-free criteria is very small.

In this proposal, we focus on retrievals of CO_2 and CH_4 over oceanic cloudy pixels. We will investigate how uncertainties in source/sink inversion models will be reduced with these data. Marine clouds that frequently occur near the top of the planetary boundary layer provide an excellent opportunity to produce a large number of high-quality retrievals that will complement existing satellite data sets.

We propose to retrieve CO_2 and CH_4 concentrations using both simulated and real data from GOSAT. Radiative transfer simulations will allow us to evaluate the theoretical limitations of the approach and to quantify potential errors. Actual GOSAT CO_2 retrievals (including seasonal and interannual variations) will be validated using ground- and aircraft-based observations and consistency with other satellite data checked through a data assimilation system. This will provide quantitative error estimates.

Specifically, we will use oxygen (O_2) A-band observations (near 760 nm) to provide information about photon pathlengths in cloudy pixels. It is important to account for additive signals, such as from chlorophyll fluorescence, that affect radiance measurements in this band. We demonstrate that in clear-sky pixels over vegetated land, GOSAT and OCO-2 can in fact be used to produce a new and unique carbon-related

product: regional-scale chlorophyll fluorescence. Our initial results with GOSAT show the first seasonal maps of chlorophyll fluorescence derived from satellite observations.

Our results may influence the observing strategy for GOSAT and OCO-2 over ocean; Currently, GOSAT points towards sunglint over ocean in order to provide a target with sufficient brightness and signal-to-noise ratio. However, clouds and aerosol can contaminate sunglint observations, and it is difficult to account for their effects owing to the wavelength dependence of glint and clouds/aerosol. Our results may show that it is beneficial to observe away from the glint.

The proposed work relates primarily to the third research theme of the Carbon Cycle Science solicitation (Advancing the scientific basis for space-based measurements of atmospheric carbon dioxide and/or methane). The NRA specifically seeks proposals to further enhance community preparedness for future CO_2 observing missions and establish a stronger scientific foundation for future greenhouse monitoring systems. This proposal is directed at these goals; It has the potential to greatly increase the number of satellite observations available for inversion schemes. Our research seeks to ensure that the most advantageous observational and retrieval scheme is implemented before launch of a future passive near-IR satellite mission.

Our chlorophyll fluorescence work also addresses the NASA/USDA-NIFA theme regarding interactions between land management and land change and the carbon cycle. Our space-based measurements specifically show links between land management and greenhouse gas (CO_2) fluxes through photosynthetic activity. Our measurements can be used to assess the resilience and vulnerability of land carbon stocks potentially affected by land change and disturbance.

Sujay Kaushal/University of Maryland/NASA Funded
Understanding and Forecasting Impacts of Climate Change and Land Use On Terrestrial Carbon Fluxes In Coastal Watersheds

Carbon (C) fluxes are rapidly increasing in many streams and rivers globally. In the U.S., agricultural activities and urbanization have substantially increased fluxes of inorganic and organic C in major rivers and estuaries. These elevated C fluxes have important consequences for regional watershed C budgets, drinking water quality and disinfection by-product formation, and regulating ecosystem processes. Although watershed inputs significantly influence biogeochemical processes and exchanges at the land-ocean interface, we know relatively little regarding predicting the impacts of land use, climate, and management strategies on watershed C fluxes. We propose to enhance and validate an existing regional earth system model, the Chesapeake Bay Forecasting System (CBFS) for predicting watershed C exports in the Chesapeake Bay region. The CBFS dynamically downscales global climate forecasts at time scales from sub-daily to interannual and decadal time-scales. It consists of regional atmosphere, ocean, biogeochemical and land dynamical models such as the Soil and Water Assessment Tool (SWAT) that are coupled together to provide comprehensive forecasts of the environmental behavior of the Chesapeake Bay region. Our primary objectives are to

predict how exports of dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and particulate organic carbon (POC) in the Chesapeake Bay watershed will change in response to land use and climate, and to provide field monitoring and validation data to adequately evaluate model results. The proposal seeks to investigate the following questions: (1) How do patterns in forestation, agricultural productivity, urbanization, and climate variability influence regional C fluxes from coastal watersheds? (2) How will different land use and management scenarios influence watershed C fluxes to rivers and regional C budgets? (3) What is the composition and quality of C transported? We will carry out the following specific tasks to address the questions: (a) Apply and modify the existing CBFS model to predict effects of land use/land cover and climate on watershed DIC, DOC, and POC fluxes in over 50 routinely monitored subwatersheds of the Chesapeake Bay at the Smithsonian Environmental Research Center site, Baltimore Long-term Ecological Research site, and Maryland Non-tidal Core Trends Sampling Stations (b) Determine key environmental forcing variables and process level coefficients for CBFS and SWAT using a combination of LANDSAT imagery mapping, information on streamflow, precipitation, soils and C:N ratios, and statistical analyses of empirical data on C exports from existing long-term monitoring stations (c) Validate environmental parameters and verify watershed C export predictions based on existing data (d) Characterize bio-optical properties of DOC using fluorescence spectroscopy and UV absorbance for validation of model products and derivation of regional relationships and parameterizations for MODIS remote sensing applications. The major questions driving our research target NASA and USDA interests including (i) interactions between land management and land change and the C cycle and (ii) adaptation, mitigation, and vulnerability within the Earth system (land, ocean, and atmosphere). Our work will result in an enhanced version of the CBFS and SWAT that will be released to the user community. A metric of our success can be transferred to regional land and water resources managers, which have emerging needs for estimates in regional C budgets, developing strategies to reduce reactive DOC exports for protection of drinking water supplies, and predicting export of alkalinity influencing ecosystem processes and coastal ocean acidification.

Ralph Keeling/University of California, San Diego/NASA Funded
Recent Trends and Physiological Constraints on Northern Extra-Tropical Ecosystems From Atmospheric and Satellite Data

Northern extra-tropical ecosystems are thought to be an important sink of anthropogenic CO2 emissions. It is important to understand how these ecosystems function and how their source/sink capacity has been changing and may change in the future. Atmospheric measurements conducted by the Scripps Institution of Oceanography and NOAA show an increase in the seasonal drawdown and release of atmospheric CO2 at northern high latitude stations. This proposal has the dual objectives of (1) estimating seasonal variations in carbon fluxes of the land biosphere in the northern extra-tropics over the past two to three decades to understand why they have been changing and (2) developing new constraints on plant physiology including stomatal conductance, gross primary production, heterotrophic respiration, and water-use efficiency of northern ecosystems in order to improve modeling capabilities.

We will investigate the causes and implications of changing carbon cycling at high latitudes by carrying out a joint synthesis of atmospheric CO_2 and satellite data documenting changes at high latitudes since the mid 1980s. The synthesis will entail using inversions of atmospheric concentrations to estimate the seasonal net fluxes of CO2 in the arctic and boreal regions. The net fluxes will be further used to constrain heterotrophic respiration by subtracting inverse calculations of net ecosystem production (NEP) from satellite-based estimates of net primary production (NPP). Any trends in surface net fluxes and respiration will be examined in the context of changes in temperature, soil moisture, etc. and also satellite-observed vegetation greenness. The project advances understanding of processes critical for forecasting future changes and potential climate feedbacks. The project also advances capabilities for optimal utilization of forthcoming CO_2 column data from the GOSAT and OCO-2 satellites by refining methods for key carbon cycle parameters from space and improving understanding of how to blend critical long-term datasets with newer satellite products to address questions pertinent to the science of global change. High latitude ecosystems may be especially vulnerable to climate-induced disturbance, suggesting some urgency in advancing this capability.

A second objective will leverage off a newly-discovered interannual signal in the oxygen isotopes of CO_2 which provides new constraints on stomatal conductance of land ecosystems at high latitudes. The signal can be leveraged to improve satellite-based estimates of stomatal conductance, providing needed verification on large spatial scales. By combining the oxygen isotopic constraints with additional physiological constraints contained in the carbon isotopes of CO_2 and CO_2 concentration, the signal can be exploited to improve estimates of gross primary production and water use efficiency (tied to 13-C/12-C fractionation factors). These parameters, which are expected to change under rising CO_2, govern growth and recovery of ecosystems and thereby are critical to forecasting future changes relevant for climate modeling and forest resource assessments.

The work in this proposal will advance the carbon-related goals of the U.S. Carbon Cycle Science Program and of related programs as directed by the NRC. Specifically, the study would help to: (1) assess the potential for large abrupt releases of carbon dioxide from arctic systems undergoing warming via a focused assessment to detect any anomalous behavior of the carbon cycle at high latitudes in recent decades, (2) assess the role of disturbances in boreal and arctic forests over the past few decades and their impacts on carbon exchanges, (3) provide constraints for improving models of forest growth needed to forecast future forest resources in a changing climate, (4) advance capabilities of modeling and monitoring land carbon fluxes pertinent to the goal of determining CO_2 fluxes for verification and assessment purposes.

Robert Kennedy/Oregon State University/USDA Funded
Integrated, Observation-Based Carbon Monitoring for Wooded Lands of Washington, Oregon, and California

Because carbon pools and fluxes on wooded landscapes are constrained by their type, age and health, understanding the causes and consequences of carbon change requires frequent observation of forest and woodland ("forest") condition and of disturbance, mortality, and growth processes. Although periodic ground- and satellite-based measures of biomass and of stand-replacing disturbance have long existed, limitations of both prevent full characterization of carbon dynamics at appropriate scales. In recent years, our team has developed tools that we now propose to expand into a large-areas carbon monitoring system that can address a range of critical and hitherto unanswerable carbon issues.

Our system integrates Landsat satellite imagery, maps of environmental characteristics, Forest Inventory and Analysis (FIA) plot data, recent small-footprint lidar data, and aerial photos to characterize key carbon dynamics in forested ecosystems across all ownerships in the states of Washington, Oregon, and California from 1985 to 2010. As heavy timber producing states undergoing rapid urbanization, increased fire and insect outbreaks, and changing climate, they serve as an excellent model to test our approach. Processes whose carbon effects will be mapped include all levels of forest harvest and fire, including both mechanical thinning and low-intensity fire, as well as insect-related mortality, post-disturbance regrowth, and land-use change away from forest types. The system will be contained in a modular structure that will allow rapid inclusion of new data for improving maps and reducing uncertainties as the system matures.

We will address a range of science and management questions, including:
1. How much have forest carbon pools or fluxes been affected by natural processes (insects, fire, wind, growth) versus anthropogenic processes (harvest, land-use change)? Are the relative impacts of those processes constant or changing as policy and climate also change?
2. How have those processes of change been distributed across forest types, ownerships, management approaches, and policy periods?
3. Has forest management intended to reduce susceptibility to insect and fire actually reduced vulnerability of carbon pools to unplanned loss a regional scale?

These science questions will be addressed by analysis of a set of key deliverables. These include annual, 30m resolution maps in Washington, Oregon, and California of:
- Forest aboveground live and dead carbon pools (Mg/ha)
- Changes in those pools from year to year
- Forest disturbance year and magnitude
- Agent of disturbance: clearcuts, partial cuts, insect mortality, fire, urbanization
- Forest regrowth rate and time period
- Forest type and condition
- Uncertainty estimation based on accumulated errors in monitoring as well as comparison with small-footprint lidar maps

Other important deliverables include robust lidar-based estimates of aboveground carbon for several study areas, a unified forest/non-forest mask for the entire region, and evaluations of best practices for integrating lidar, Landsat, and FIA plot data.

The system will also be useful for:
- State agencies tasked with carbon monitoring
- Federal land management agencies
- Carbon modelers to train, calibrate, and validate the process-based models needed for future scenario building and fors decision support

The project addresses both sections 3.1 and 3.4 of the A.5 proposal call by 1) addressing the effects of land management and land use on carbon, and 2) developing the scientific foundations and analytical approaches for monitoring effects or efficacy of management-based carbon mitigation strategies.

Marcy Litvak/University of New Mexico/NASA Funded
Improving The Estimation of Carbon Stocks and Fluxes In Semi-Arid Ecosystems of The Southwestern Us Using Full-Waveform Lidar Measurements

Improving the estimation of carbon stocks and fluxes in semi-arid ecosystems of the southwestern US using full-waveform lidar measurements. PI: M. Litvak

The magnitude of carbon fluxes through arid and semi-arid ecosystems is considered modest, but integrated over the ~40% of the global land surface covered by these ecosystems, the total carbon stored is almost twice that in temperate forest ecosystems. Understanding where carbon is stored in these ecosystems and how carbon sequestration and exchange with the atmosphere will respond to climate change is crucial given the extent of these ecosystems and that the southwestern US is predicted to experience warming of up to 4°C and substantial declines in precipitation over the next century. A critical tool for policy makers determining safe levels of green house gases in the atmosphere are Earth system models capable of predicting the response of the biosphere to climate change, given the potential for carbon cycle feedbacks exacerbating greenhouse-house-gas induced climate change is large. However, a recent comparison of the carbon dynamics forecast by a number of different Earth system models exhibited great variability on decadal timescales, indicating considerable uncertainties remain.
The purpose of this proposal is to reduce uncertainties regarding regional carbon dynamics in the Southwestern US by combining a more accurate estimate of vegetation structure using full-waveform lidar to direct measurements of ecosystem-atmosphere carbon exchange across a network of eight eddy covariance tower sites in TX and NM. We will do this within a model-data fusion (MDF) framework to improve estimates of regional carbon stocks and fluxes and produce a land surface model (LSM) capable of making predictions about the response of C dynamics in semi-arid ecosystems to changing climate and disturbance.
Lidar remote sensing has become a critical instrument for obtaining information on vegetation structure and a number of studies have tested the use of waveform lidar for

characterizing structure and estimating above ground biomass via height-diameter allometric relationships in temperate and tropical forests. However, in semi-arid environments, the dominant species exhibit more complex allometric relationships due to the multi-stemmed architecture at the base of the tree. In this proposal we will investigate how laser waveform derived parameters can provide a more accurate estimation of vegetation structure (above ground biomass, height and leaf area) across a range of semi-arid ecosystems, providing a critical test of the potential of space-based full-waveform lidar in these environments. We will also investigate the impacts of sensor resolution and spatial aggregation on measurement uncertainty, and how this is propagated into model uncertainty when used in model initializations.

This research responds directly to the NRC report, Restructuring Federal Climate Research to Meet the Challenges of Climate Change (2009), by: (i) collecting data needed to document, understand and predict the effects of climate change which will be made available through the FLUXNET data base, supporting the integrative analysis made possible by Ameriflux; and (ii) helping to support the development of a new generation of coupled Earth system models through providing more accurate observed land surface state for model initialization and testing, further developing and constraining model parameterizations. By assessing carbon stocks and fluxes across a range of biomes (natural and managed forest and rangeland) where ecosystem services are under threat from disturbance and pest outbreak due to global change related drought or woody encroachment, we are addressing important scientific-societal issues relevant to carbon cycle science in the Southwestern US.

Patrick Louchouarn/Texas A & M University at Galveston/NASA Funded Examining The Relationships Between Land Use Change, Wetland Alteration, and Carbon Sequestration In The Gulf of Mexico

Our proposed study will examine the relationship between land use change, wetland vegetation shift/loss, and carbon (C) sequestration on the coast of the Gulf of Mexico (GOM). By combining field calibration with analysis of remote sensing imagery to detect land cover change, we aim to better understand the amount of carbon sequestration capacity lost from the alteration of naturally occurring estuarine wetlands over the last decade.

Carbon sequestration is an important ecosystem function in all vegetated habitats, and increasing evidence suggests that tidal wetlands may play a particularly key role in regional to global C budgets. Although tidal wetlands store ~10% of worldwide soil C pools (Schlesinger, 1995; Chmura et al., 2003), we know very little about the mechanisms that control this storage process. In the conterminous U.S., and over the next 20 years, the total burial flux of C in tidal wetlands (4.0-4.4 Tg/yr; Chmura et al., 2003; Brigham et al., 2006) could represent from as little as ~3-18% to as high as ~75-80% of the potential soil C sink estimated over the same period in agricultural soils (0.5-1.1 to 2.8 Pg; Cole, 1996; IPCC, 2001; Van Oost et al., 2007), despite comprising <0.5% of their surface area. Furthermore, estimates of C accumulation rates (fluxes) in wetlands are usually derived from large-scale simplifications (Chmura et al., 2003; Brigham et al., 2006) and thus need further revisions to accurately quantify C sequestration potential in these habitats.

Because the large-scale C stocks in the surface meter of tidal estuarine wetlands, substantial losses or alterations of these ecosystems could rapidly offset any management of croplands even at its highest efficiency. Despite localized restoration efforts, estuarine wetland loss continues at a rate of at least 5,700 acres/year, with the majority of that loss occurring on the GOM Coast (Dahl, 2006). Furthermore, in some areas, marsh grasses are being displaced by mangrove trees, possibly as a result of changes in local climate patterns. Analysis of remote sensing imagery over time can quantify the magnitude of past changes in wetland type and areal extent, due primarily to population growth and development along the coast, but requires field calibration to assess changes in the ability of these wetland systems to effectively sequester C.

The goal of this proposal is to calibrate NASA satellite imagery to characterize C storage within diverse estuarine wetland ecosystems (tidal marshes, mangroves), as well as the influence that land-use change and climate-induced ecosystem shifts (salt marsh to mangrove succession, wetlands to open water) may have on both the pools and fluxes of C in these systems. Following quantification of C sequestration potential on the Texas coast, we will be able to scale up to estimate C storage potential in tidal estuarine wetlands throughout the entire GOM region.

Our specific research objectives are to:

1) Quantify C sequestration in coastal wetlands with special emphasis on marsh and mangrove plant communities along the Texas coast.

2) Identify and measure the shift in vegetation structure that has occurred in estuarine wetlands over the last decade.

3) Identify and measure the loss of naturally occurring estuarine wetlands over the last decade from land use change along the coast.

4) Measure the amount of carbon sequestration capacity lost due to recent human-induced changes in the landscape.

Our proposed research is an ideal fit for the Carbon Cycle Science investigations within the NASA Earth Science Program because it will improve understanding of the global C cycle and quantify changes aquatic C storage “in response to land use and land cover change, and other human activities and natural events.” By investigating the interactions between land use/land cover change and the C cycle, we seek to develop applications that directly inform resource management, policy development, and decision-making.

Charles McClain/NASA Goddard Space Flight Center/NASA Funded
Assessment and Impact of Carbon Variability In The Nordic Seas

In areas where deep water formation occurs, such as the Nordic Seas, a relatively rapid transmission of atmospheric gases to the deep ocean is expected. In the North Atlantic, one of the important regions of deep water formation is the Greenland Sea. Together with the Iceland and Norwegian Seas, the Arctic Ocean, and the Barents Sea, it makes up a region known as the northern limb of the Atlantic thermohaline circulation, which is estimated to give rise to a significant preindustrial inter-hemispheric transport of inorganic carbon directed from the northern to the southern hemisphere. Therefore, it is important to study the carbon dynamics in the Nordic Seas as they are an integral part of the global carbon cycle. Observational studies report significant variations of the ocean CO_2 sink in the North Atlantic, and suggest a reduction of the atmospheric CO_2 uptake

during the last two decades, especially in the Subpolar and Nordic Seas. Modeling studies reveal that surface ocean water mass properties and CO_2 system variables exhibit substantial multiannual variability on sub-basin scales in response to wind-driven reorganization in ocean circulation and surface warming/cooling. The temporal evolution of the CO_2 system is influenced by anthropogenic trends and natural variability of the vertical inventory of carbon stocks. The phase of the North Atlantic Oscillation (NAO) plays a significant role in modulating the North Atlantic Current transport of subtropical waters into the eastern basin and thus impacting on surface ocean CO_2 uptake. The intense spring-summer phytoplankton blooms that characterize the Nordic Seas not only support the commercially valuable fishing grounds through the foodweb via grazing by zooplankton, but also play a major role in the uptake of atmospheric CO_2. Major changes in environmental conditions can significantly alter the physical-biogeochemical interactions in the region and consequently produce an impact on the carbon variability. We propose to use a combination of remote sensing data analysis, numerical model experiments, and in situ data to assess the impact of carbon variability in the Nordic Seas. We are already working with our European collaborators on a similar NASA-funded study with its major focus in waters south of Iceland. These collaborators have been providing, and will continue providing, invaluable carbon-related data sets and regional expertise for the proposed study. We propose to extend the scope of our work to other areas, such as the European Sub-Arctic, waters in the vicinity of Svalbard, and the Barents Sea. A 3D ice-ocean model, which covers the Arctic Ocean and the sub-polar North Atlantic, will be used to drive a 1D ecosystem/carbon model which will be applied to key biogeochemical provinces within the study regions. SeaWiFS and MODIS data analysis will include Chl-a, POC, PIC, CDOM (a proxy for DOC inputs from Arctic rivers), phytoplankton carbon (from backscatter), and derived products such as net primary production (NPP) and PIC production. While SeaWiFS and MODIS are primary sources of data, the Indian OCM-2 and VIIRS are also potential sources of data within the time frame of the investigation. The analysis will be linked to algorithm development/improvement (NPP, pCO_2) and validation of model simulations. Recent studies have shown that satellite altimetry helps explain patchy changes in hydrographic carbon measurements. We will include satellite altimetry analysis in our study to address this issue. The proposed work addresses three of the five research themes solicited by NASA (items 2, 4, and 5, section 3 of A.5): (2) ocean acidification; (4) adaptation, mitigation, and vulnerability within the Earth system; and, (5) synthetic and integrative research to advance the carbon-related goals of ongoing research activities under the U.S. Carbon Cycle Science Program and the carbon-related goals and objectives of related national and international programs.

Galen McKinley/University of Wisconsin - Madison/NASA Funded
The Impact of Thermocline Induction on Decadal Variability of The North Atlantic Carbon Sink

Remotely sensed and in situ data suggest that ocean biological productivity and carbon uptake are changing, but we are challenged to distinguish between anthropogenically-forced trends and natural decadal timescale variability. We need to enhance our capacity

to make these distinctions so that we can better inform climate change mitigation and adaptation decision-making.

In this proposed work, we will quantify the impact of ocean circulation-driven variability in carbon and nutrient induction on observed changes in surface ocean productivity and air-sea CO2 fluxes in the North Atlantic. Induction, an injection of fluid and tracer from the permanent thermocline across the sloping base of the seasonal mixed layer, has been shown to be many times larger than Ekman upwelling and dominant to surface ocean nutrient renewal (Williams et al. 2006). Based on preliminary results, we propose that a spin-down of the subpolar gyre, associated with the negative trend of the North Atlantic Oscillation from the mid-1990s to the mid-2000s, led to substantial reductions in induction of nutrients, dissolved inorganic carbon (DIC) and alkalinity (ALK). In turn, the declining induction caused (1) productivity declines, as observed in the satellite record, and (2) declines in surface ocean DIC and ALK that have caused a pCO2 reduction that has approximately balanced pCO2 increases driven by warming sea surface temperature (SST) over the same period.

We will (1) perform a joint analysis of satellite and ocean state estimates, (2) perform idealized modeling experiments, and (3) analyze realistic hindcast models in order to address the following science questions:

- Question 1: To what degree does nutrient, DIC and ALK induction at the base of the wintertime mixed layer contribute to surface ocean tracer budgets, their temporal variability, and related biogeochemically-relevant fluxes?
- Question 2: How do subpolar gyre spin-down and spin-up modify tracer induction?
- Question 3: What is the net effect of subpolar gyre spin-down and spin-up on the carbon sink of the North Atlantic?

As requested under NASA ROSES 2010 A.5. Carbon Cycle Science, this work helps to answer "How large and variable are the dynamic reservoirs and fluxes of carbon within the Earth system and how might carbon cycling change and be managed in future years, decades and centuries?" This is Synthesis and Integrative Research (section 3.5) that is in support of the currently-identified priorities of the Ocean Carbon and Biogeochemistry / Ocean Carbon and Climate Change program.

Jason Neff/CU Boulder/USDA Funded
Carbon Management On Public Lands In The Intermountain West: Multi-Scale Analysis of Carbon Stock Responses To Human and Natural Disturbances.

In this proposal, we describe an integrated multi-scale approach to the evaluation of carbon stocks and fate under different management on public lands in the Intermountain West. We have developed this proposal in close collaboration with the US Department of Agriculture (USDA) Forest Service and the Department of Interior (DOI) Bureau of Land Management. There are four primary objectives in our work and these are 1) the Analysis of forest and woodland carbon stocks across elevational gradients in Southwest Colorado and eastern Utah, 2) the Evaluation of changes in forest and woodland carbon

associated with land management activities including fire mitigation, and forestry, 3) the Projection of management impacts on carbon balance using ecosystem carbon models, and 4) the Integration of carbon into land management decisions including evaluation of potential implications of different federal approaches to carbon management. The work proposed here uses remote sensing and field biomass measurements to develop regional carbon maps for federal land management centers in Colorado and Utah. At these sites, we also will monitor changes in carbon stocks with management using ground based, data-collection techniques and use existing USFS models of forest biomass change to project carbon accumulation through time. In all of our analysis, monitoring, and modeling work, we will deal directly and explicitly with error and uncertainty and all spatial or temporal projections of carbon will include uncertainty bounds. Finally this study includes the development of new decision support tools for carbon management that will reside in federal land management databases at our study sites. We also recognize that federal carbon management policy and interaction with existing land management policy is uncertain and likely to remain so for some time to come. Accordingly, our study includes not just the development of decision support tools but also an explicit study of decision-making. This study will help to identify the barriers and complexities involved in integration of carbon management into broader federal land management goals.

The work described in this proposal takes advantage of existing technologies and analysis capabilities. The tools and approaches described here, including our remote sensing approaches, are well tested and commonly used. Our choice to use common, rather than truly cutting edge tools, is intentional and reflects the reality of decision making within federal land management agencies. This proposal is directed toward the joint NASA-USDA component of the carbon cycling NRA and our approaches are ones that already are used in the federal land management context and which will be familiar to land managers in the USFS and other agencies. Where this proposal breaks new ground is in the integration of these techniques across scales and in the explicit and serious consideration of how error and uncertainties propagate up to and through decision-support tools. Our work is based in strong, ongoing collaborations with federal land management centers in Colorado and Utah and we (and our federal partners) view this work as an opportunity to use these centers as “test cases” for broader federal carbon management activities if or when federal carbon legislation is established. We have a strong existing commitment to educational outreach including joint academic/federal land management internships and we will seek to expand these opportunities with the work proposed here.

Ross Nelson/NASA Goddard Space Flight Center/NASA Funded
A Lidar-Radar-Optical Data Fusion Approach For Estimating The Aboveground Carbon Stocks of North American Forests: Means and Uncertainties At Regional To Continental Scales

Forests are the most important terrestrial carbon reservoir and will influence and be influenced by climate change. For this reason, monitoring forest carbon stocks at regional and continental scales will be an important element of a future climate observing system. Such a forest carbon monitoring capability will also be a key input to new generations of

coupled Earth system models and will provide a means of validating the large-scale performance of various adaptation and mitigation strategies. The proposed research will build on a methodology that we have developed in previous NASA-funded projects of combining data from the Geosciences Laser Altimetry System (GLAS), which has been flying on the ICESat satellite, with data from airborne lidar, ground plots, land cover classifications, and digital elevation models to predict aboveground forest carbon stocks. Whereas we have previously applied this approach only to northern forests, we adapt our methodology in the current proposal so that we can move our work to the next logical step and apply it to the entire North American continent. The field efforts will be concentrated on forests in the contiguous US and in Mexico.

The basic approach makes use of recently measured, geolocated forest inventory plots which are then over flown with a portable airborne lidar. This permits us to relate lidar heights to the aboveground carbon stocks and biomass of the plots. We then fly the airborne lidar over the GLAS ground tracks, allowing us to statistically relate the airborne laser data to the satellite data. The full set of quality-filtered GLAS data can then be extrapolated to larger spatial scales by combining this information with land cover classification and topographic data. Since our previous experience has shown that GLAS does not perform well for estimating biomass of open stands with aboveground biomass <20 Mg ha-1, we will develop an image processing procedure that can integrate the GLAS information with L-band radar data from PALSAR and from the MODIS Vegetation Continuous Fields (VCF) canopy closure product. We will use the VCF optical product to establish a threshold below which PALSAR-based estimates start to replace the GLAS-based estimates. We will also develop a statistical framework for integrating the different satellite information sources into a coherent methodology for estimating the amount and the uncertainty of aboveground forest carbon stocks for all of North America as well as its principal ecoregions. The statistical framework will also allow us to quantify how future changes in land cover and land use in the different regions of North America are likely to impact aboveground carbon stocks. This project will make a significant contribution to the continental-scale components of the North American Carbon Program (NACP) as well as the US-Mexican-Canadian collaboration of the Carbo-NA Program, both high priority elements of NASA's and USDA's carbon cycle science programs.

Lesley Ott/University of Maryland Baltimore County/NASA Funded
Observing System Simulation Experiments To Optimize The Assimilation of High Resolution CO_2 Observations From Space In The Presence of Clouds

High-resolution space-based observations of column CO_2 represent a major advancement in our understanding of the carbon cycle and are expected to help constrain source and sink distributions. However, both the GOSAT and OCO instruments are limited by the presence of clouds. Such observations present a unique challenge to data assimilation studies because clear-sky observations alone may not be representative of the area covered by a global model grid cell containing both clear and cloudy regions. We propose to conduct a series of observing system experiments (OSSEs) to create new methods for assimilating GOSAT and OCO observations. OSSEs include the simulation

of a 'nature' atmosphere that is sampled to produce synthetic column CO_2 estimates comparable to those yielded by satellites. Synthetic observations are then assimilated and their ability to draw assimilation runs toward the true atmosphere evaluated. OSSEs have the advantage of providing a controllable framework in which data properties and the 'true' state of the atmosphere are known in order to assess assimilation techniques. While a number of OSSEs have been performed to understand how OCO and GOSAT data will inform flux estimates, none have focused on developing techniques to assimilate clear-sky observations into a cloudy atmosphere.

This work will employ the GEOS-5 data assimilation system which has been previously been used as a tool for estimating global distributions of CO and O_3 and is currently being used to assimilate AIRS CO_2 data. Synthetic observations will be derived from a high-resolution (0.125°) GEOS-5 simulation in which prescribed CO_2 flux distributions are disaggregated based on 1-5 km resolution satellite data from a variety of sources. These synthetic observations will be assimilated into GEOS-5 simulations (0.5°) with a focus on evaluating how simulated concentrations are constrained when clouds are present in the coarse grid cell. Experiments will include alterations to assumed observation error and bias, different methods for aggregating observations prior to assimilation, and alterations to the model's convective scheme which allow for separate in- and out-of-cloud trace gas profiles. Informed by our evaluation of assimilation techniques, we will assimilate real GOSAT and AIRS data at 0.5° providing a high-quality assimilated dataset at unprecedented horizontal resolution.

Faiz Rahman/Indiana University/NASA Funded
Carbon Dynamics, Land Cover Change, and Vulnerability of the World'S Largest Coastal Mangrove Ecosystem To Climate Change

Mangroves are complex ecosystems providing a variety of ecosystem services including storm protection, fisheries resources, influences on water quality and a significant global C sink. Recent work by the PIs have found that the C pools of mangroves are among the highest in the world. Further, rates of deforestation and land cover change of mangroves are the highest of any forest cover type in the Asia Pacific. Yet, no comprehensive studies exist to quantify C losses as well as the declines of other ecosystem services associated with land use/land cover change of mangroves in Asia.

The Sundarbans is the world’s largest single block of mangrove forest, covering approximately 10,000 km2 of the Ganges delta along the coastal areas of India and Bangladesh. It is the home of a remarkable array of biodiversity including the Bengal Tiger, Ganges River dolphin, Saltwater crocodile, and hundreds of species of birds and mammals. It is also sustainably utilized by millions of people but threats from both land cover change and climate change threaten this sustainability. Sea-level rise, increases in number and severity of cyclones and alteration of water flows from the Himalayan headwaters are global change influences of concern. Sea level rise alone is predicted to potentially displace as many as 35 million people in the region by the middle of the 21st century. Land cover change may strongly interact with climate change to affect

sustainability, function as a global carbon sink, and regional biodiversity of the coastal regions of tropical Asia.

Despite the values and vulnerability of the mangroves of the India/Bangladesh coastal region, very little data exist, or have been collected, on the spatial and temporal distribution of above and belowground carbon pools, their dynamics, and the impacts of anthropogenic and natural disturbances on this vulnerable ecosystem.

We propose to assess and map the existing carbon stocks of the Sundarbans by a combined use of optical, radar, and lidar remotely sensed data with ground-based and modeling studies of biomass and carbon dynamics of land use/land cover change. We will explore the impacts of disturbances on the carbon pools and ecosystem services provided by these mangroves, and produce historic maps of their coverage as well as carbon loss. Using predictive modeling we also plan to produce future scenarios of vulnerability maps and adaptive capacity metrics of Sundarbans and the adjacent coastal areas of the Ganges/Brahmaputra delta.

James Randerson/University of California, Irvine/NASA Funded
Global Carbon Emissions From Fires: Improving Our Understanding of Interactions Between Land Use, Fires, and Climate Change

A changing fire regime represents an important vulnerability for terrestrial carbon stocks in many biomes. Here we propose to develop new ways to quantify fire carbon emissions associated with different types of land management using satellite observations. Our work plan has the following four objectives.

1. In tropical forests, we will develop new estimates of carbon emissions from understory fires and from fires associated with small and large-scale deforestation clearings.

2. Globally, we will quantify post-fire trajectories of ecosystem recovery to improve the capacity for linking fires to different forms of land use and also to improve tree mortality and combustion completeness parameterizations.

3. We will reduce uncertainties associated with the attribution of fire emissions to different forms of land management using trajectory, fire size, and other satellite information.

4. We will assess the vulnerability of terrestrial carbon stocks to future changes in the fire regime and identify opportunities for mitigation. As a part of this effort, we will separately estimate the climate sensitivity of fire carbon emissions associated with different types of land management during the contemporary era (1997-2010) and combine this information with predictions of future climate from IPCC AR5 models.

Another important project goal is to improve our Global Fire Emissions Database (GFED) time series of burned area and fire carbon emissions using multiple satellite and field datasets for calibration and validation. We specifically plan to develop and release a

16 year time series of global fire carbon emissions (1997-2012) derived from MODIS observations, with a monthly time step and a 0.25° spatial resolution during 2000-2012. Other key deliverables will include the first global maps of pan-tropical understory fires, the first global maps of fire recovery times and fire sizes, improved attribution of fire carbon emissions to different forms of land use and land use change, and information about climate-induced changes in the fire regime during the 21st century. Our project is a collaborative effort by scientists from UC Irvine, Columbia University, Goddard Space Flight Center, Duke University, and Vrije Universiteit Amsterdam.

Michael Rawlins/University of Massachusetts/NASA Funded
Synthesis and Integration of Recent Research Characterizing The Carbon Cycle of Northern Eurasia

Northern Eurasia is characterized by large carbon storages and seasonal fluxes, through both sinks and sources, and is thought to be particularly susceptible to climatic change. In recent decades the region has experienced warming and attendant change in carbon cycling, with further alterations likely to convey positive feedbacks to global greenhouse gas forcing. The carbon cycle of the Arctic drainage region of northern Eurasia is tightly linked with surface water and permafrost dynamics that, in turn, are influenced by the extensive network of lakes and wetlands across the region. We propose to synthesize the results of recent projects, focused on the carbon cycling of the Arctic basin draining the North Eurasian Earth Science Partnership Initiative (NEESPI) region, within a set of linked models to estimate the magnitude, potential future changes, and associated uncertainties in carbon sinks and sources. The modeling constructs central to this project have been developed to simulate CH_4 emissions from sources such lakes and wetlands, as well as other CO_2 sources/sinks. They also leverage remote sensing data for characterization of surface water and forest/boreal dynamics. Lake methane emission data and satellite-derived net primary production, both to be drawn from recent projects, will be used in a synthesis analysis of the region's carbon cycle and for integration within the modeling framework. Fields derived from remote sensing from AMSR-E, MODIS, QuikScat and Landsat satellites include the inundation water fractions, landcover type, and net primary production. A unique aspect of our modeling synthesis and integration centers on the use of these remote sensing data to capture key water and carbon cycle processes operating on relatively fine spatial and temporal scales. The overarching goals of the study include quantifying carbon cycle dynamics from the terrestrial land surface, estimating the potential associated responses to continued warming, and gaining an improved understanding of the controlling physical processes governing the region’s carbon cycles.

This study addresses goals of the U. S. Carbon Cycle Program and the U. S. Global Change Research Program, and follows several NASA Roadmaps though our efforts to document and understand how the global carbon cycle and terrestrial ecosystems are changing, quantify carbon fluxes; and provide useful projections of future changes in carbon cycling.

Peter Raymond/Yale University/NASA Funded
United States Stream and River CO_2 Evasion

Streams and rivers have been described as the arteries of the continents, removing terrestrial by-products and delivering them to the ocean and over the past decades researchers have demonstrated the utility of using stream measurements for integrating watershed biogeochemistry. Recently, members of the scientific community have been emphasizing the need to integrate the lateral flux of stream carbon into terrestrial budgets. We argue that this effort will be useful not only from a carbon budget standpoint, but will also inform us on drivers of watershed biogeochemistry. We have recently been compiling morphological and chemical data from the United States that we argue can be used to produce important data products to link streams and rivers to the countries efforts to refine and understand its carbon budget and to further our understanding of stream biogeochemistry. Namely we propose to produce new annual and seasonal discharge, stream morphology (i.e., width, depth, and velocity), and CO_2 evasion maps for the entire U.S. stream network.

A cursory look at these data indicates that the United States stream CO_2 flux is big enough to consider (~0.25Pg yr-1). This flux also has spatial and seasonal variation that can be used to study landscape and climatic controls. As part of our effort to understand landscape controls, we propose to look for linkages between metrics commonly used in terrestrial carbon models (e.g., NDVI) in order to facilitate the incorporation of stream fluxes. An exciting part of the proposed work is the availability of large data sets for a country wide effort. Our response variables include ~12,900 stream/river sites where we can calculate CO2 and ~8,800 stream sites with morphological measurements (width, velocity, and depth). The morphological measurements just came on-line in their entirety this January.

The proposed effort represents a new collaboration between three scientists at Yale with complimentary expertise (Peter Raymond (stream/carbon cycling), Karen Seto (remote sensing) and Yongtao Guan (spatial statistics)). The proposed study is aimed at the fifth research theme of the Carbon Cycle Science solicitation, "synthetic and integrative research to advance carbon-related goals of ongoing research activities under the U.S. Carbon Cycle Science Plan" and is in direct response to recent work by the NACP interim synthesis to integrate streams and rivers into terrestrial carbon budgets.

Herman Shugart/University of Virginia/NASA Funded
Synthesis of Forest Growth, Response To Wildfires and Carbon Storage For Russian Forests Using A Distributed, Individual-Based Forest Model

We propose to develop a synthesis that links advances in ecosystem modeling and remote sensing in an integrated assessment and forecasting system with rigorous testing against ground observations. Our proposed research focuses on the Russian boreal forest, the largest forest region on Earth and a tremendous repository of terrestrial organic carbon which is widely expected to undergo major transformations with climate change. Siberian summers in the past century were the warmest of the past millennium, and future

climate scenarios indicate continued warming, by some accounts between 2-10°C by 2100. The available estimates of carbon storage and flux in the Russian forest are divergent and contribute significantly to uncertainty of global estimates. Our principal objective is to predict the response of the Russian boreal forest to changing climatic conditions and disturbance regimes. The proposed synthesis of results from three NASA-funded research groups working in the Russian forest will perfect our capability to estimate carbon stores and flux and assess the impact of climate change on future carbon dynamics. We will first develop a continental-scale dataset characterizing the disturbance and regeneration over the past 30 years using a combination of moderate resolution satellite data and products. An individual-based forest model that successfully simulates the species and biomass dynamics of the Eurasian boreal forest, FAREAST, will be expanded to include dynamic simulation of carbon in a coarse woody debris reservoir and multiple regeneration rates following disturbance. The new version of the model will be tested against independent ground data, and then combined with disturbance and regeneration datasets and tree cover attributes from a new MODIS-based regional land cover map (NELC) to characterize carbon stores and fluxes circa 2010 at 500 m resolution. Estimation error will be quantified using standard deviations of predictions from multiple FAREAST model runs, an accuracy assessment of disturbance and regeneration estimates against test site data and a determination of overall error in resulting carbon stores and flux estimates. Future changes will be projected from the present state using the fire occurrence model and FAREAST model outputs for future climate associated with a diverse range of emission scenarios to define the upper and lower limits of uncertainty from three General Circulation Models. This set of projections will be compared with outputs from several recent Dynamic Global Vegetation Models to evaluate the degree of agreement among models in estimating change in the dynamic carbon reservoirs contained in the Russian forest. The proposed research directly addresses the major goal of the NASA Earth Science Research Program by quantifying changes in terrestrial stocks and fluxes of CO_2 in response to human activities, natural events, land use and land cover change under the influence of climate change. It is aimed at advancing the carbon-related goals and objectives of major international programs, notably the Northern Eurasia Earth Science Partnership Initiative (NEESPI) under the International Geosphere-Biosphere Programme (IGBP) and World Climate Research Programme (WCRP). Furthermore, it will augment the efforts of the North American Carbon Program (NACP) by quantifying the uncertainty in the Northern Eurasian boreal stocks and thus improve estimates of carbon storage and fluxes globally.

David Siegel/University of California, Santa Barbara/NASA Funded
A Mechanistic Approach Towards The Remote Assessment of Carbon Export by Sinking Particles in the Open Ocean.

Carbon export, the vertical transport of organic carbon from the surface ocean into its interior via sinking particles, is a critical part of the upper ocean carbon budget. However, our ability to remotely assess carbon export rates globally remains primitive at best as carbon export is most commonly estimated as the product of remotely sensed values of net primary production (NPP) multiplied by a very simple export-ratio model. These models may provide a reasonable assessment of present state of mean carbon

export, but they will not assess changes in export as these are purely empirical models and none of the critical information about mechanisms driving export are included. To make that next step towards a mechanistic assessment of ocean carbon flux we need knowledge of upper ocean particle source material concentrations and characteristics and knowledge of how physical oceanographic processes alter upper ocean particle fields and package suspended materials into sinking particles that are exported into the ocean interior.

Here we propose a coupled field, imagery analysis and modeling program aimed at understanding the mechanisms driving carbon export and developing novel tools for its remote assessment. Specifically, we will conduct two ~3200 km long meridional transects across the North Atlantic (~40 to 20ºN) collaborating with the Bermuda Atlantic Time Series (BATS). We will sample carbon export (via 234Th disequilibria) from vertical water samples and surface samples from underway collection (with 10 km spatial resolution). Concentrations of the radioisotope thorium-234 are an excellent index for euphotic zone particle removal as measured by its disequilibrium with its parent (238U) and recent technical advances enable its high spatial resolution sampling from a ship's underway flow system. Upper ocean particle concentrations and characteristics will be sampled by measuring inherent optical properties, phytoplankton abundances and pigments, size-fractionated inherent optical property and chlorophyll concentrations, particulate organic carbon, transparent exopolymer particle (TEP) concentrations, and the particle size distribution (PSD) spectrum. These observations will be made both underway from the ship's surface underway system and as vertical profiles. This work will constrain the types and concentrations of particles and processes that are leading to particle export. Satellite ocean color observations of inherent optical properties and the PSD will be integrated into the interpretation of the field observations.

A key element of our proposal is the simultaneous observations of particle export and source material characteristics and the physical drivers of particle aggregation. Recent modeling studies have shown that Lagrangian Coherent Structures (LCSs) can be determined from merged satellite altimetry observations. LCSs define the attracting and repelling surfaces in 2-D flow fields and provide an excellent, diagnostic tool for assessing regions where submesoscale particle aggregation will occur as well as vertical motions at fronts. The relationships among LCS locations and intensities will be evaluated using observations from the ship transects and from advance ocean color data products. The proposed combination of high-resolution field observations, remote sensing data analysis and assessment of LCSs is a unique feature of our work.

This proposal responds to Section 3.5 (Synthesis and integrative research) in the Carbon Cycle call for proposals.

Erica Smithwick/Pennsylvania State University/NASA Funded
Influence of Disturbance and Seasonality on Regional Carbon Flux Upscaling

We propose to investigate the effects of disturbance and seasonality on carbon flux upscaling efforts in northern temperate forests, which is directly relevant to research theme A3.1 (Interactions between land management and land change and the carbon cycle) and theme A3.5 (Synthesis and integrative research). Our goal is to improve diagnostic CO_2 flux estimates for northern temperate forests using spatial and temporal

variation of historical disturbance and seasonality - two key unknowns in regional scale terrestrial C exchange. This work builds on current research funding ("Probabilistic carbon flux upscaling across a northern forest ecoregion", Davis, Bolstad, Desai, Heinsch, Running and Keller, investigators) in which eddy flux tower data was integrated with sub-pixel scale forest complexity using a light use efficiency model in a Bayesian/Markov Chain-Monte Carlo framework to reduce uncertainty in MODIS NPP outputs. This effort has demonstrated considerable progress towards uncertainty evaluation using model-data fusion. Yet, persistent and unresolved uncertainty in carbon flux estimates remain that we expect reflect regional variation in C flux with stand age and season. Therefore, in this project we propose to answer 3 questions (1) Does incorporation of variation in physiological model parameters improve seasonal and interannual CO_2 flux hindcasts from eddy flux towers? (2) Does incorporation of stand-replacement and partial disturbance processes from remotely sensed observations improve yearly to decadal CO_2 flux hindcasts from eddy flux towers? And (3) To what degree does model-data integration aid regional and landscape decision-making for forest C storage management? We hypothesize that improvements in CO_2 flux hindcasts will occur after accounting for seasonal and interannual variation of key physiological parameters, such as maximum photosynthesis and quantum yield and that residual errors in CO_2 flux tower assimilations can be partially accounted for by regional patterns in disturbance observable with NASA remote-sensing products. We expect that model-data integration can be used to prioritize geographic location and timing of active forest C management activities in the face of climate change. We will explicitly compare NASA remote-sensing platforms (Landsat and MODIS) and disturbance detection algorithms (VCT and LandTrendr). Our data-fusion approach will help diagnose and attribute variability in landscape C flux due to input data (disturbance and landcover) as well as parameterization of a light response model that is sensitive to seasonal variation in photosynthesis (driven by variation in EVI and climate). Finally, we will compare our results to the MsTMIP site and regional scale model intercomparison effort and use MsTMIP data to drive our model where appropriate (Collaborators Huntzinger, Michalak). Our uncertainty analysis will aid the MsTMIP synthesis effort. Data will be archived at ORNL DAAC (Collaborator Robert Cook). Ultimately, our work will contribute to the "end-to-end" mission of the NRC (2009) report by directly contributing to a priority landscape identified by the USFS for climate change management climate change.

Thomas Spies/USDA Forest Service/NASA Funded
Tradeoffs Among Carbon and Other Ecosystem Services Associated With Different Forest Management Practices

We propose to use integrated forest monitoring and simulation models to evaluate trade-offs among carbon, and ecosystem services in a forest region. Our objectives are: 1) evaluate carbon and ecosystem services produced under alternative future scenarios defined in terms of climate change and forest management strategies for the Pacific Northwest and northern California; 2) evaluate tradeoffs among select ecosystem services (carbon, biodiversity indicators, and wood products); and 3) work with stakeholders from a variety of agencies and organizations to improve the value of the work to society

and better communicate our findings. The project will reveal opportunities to alter management to improve the production of multiple ecosystem services. The work will also address the effect fuel management on carbon in fire-prone landscapes, which is a subject of major scientific uncertainty.

We will use a suite of established models including LandCarb 3 and ForProd 2 (landscape characteristics, carbon, and wood products), a forest stand vegetation simulator (FVS), and wildlife habitat capability models. The project has both retrospective and prospective dimensions. Historical and alternative future relationships among carbon (storage and flux), wildlife habitat (for several different species) and wood products will be characterized in sample landscapes representing 8 of the major forest ecoregions of the study area. The project will rely on annual resolution Landsat products to characterize historical changes in forest conditions associated with disturbance (both natural and management) and forest re-establishment rates. The carbon models will use this information to predict changes in carbon stores both in the forest and in wood products. Recently acquired Lidar data will be used to check the predictions of the forest models in terms of growth, biomass and carbon stores, and wood production. This retrospective component will prototype a remote-sensing-ecosystem monitoring approach and will also establish a baseline to evaluate the landscape simulation models. We will then project and evaluate 10 alternative future climate and management scenarios, comparing levels of ecosystem services among different management approaches. The stand development simulator will be used to evaluate how silvicultural prescriptions affect the relationship between carbon and forest structure. The results of these stand-level analyses will inform how different carbon management strategies impact patterns of forest structure at landscape and regional scales. Wildlife habitat suitability models will then be developed for focal species representing a range of biodiversity potentials. Tradeoff analysis will be conducted using the scenario simulations as data points.

The work is highly relevant to NASA and the NRA objectives of Carbon Cycle Science and Applied Science. First, it seeks to improve understanding of the carbon cycle as it relates to land use and land cover change. Second, it encompasses the multiple temporal and spatial scales needed to understand these issues. Third, it considers tradeoffs between carbon and other ecosystem services and adaptation approaches (e.g. thinning). Fourth, it examines interactions of climate change with management. Fifth, remote sensing data and tools are central to the work and lay the foundation for further relevance of NASA science to national and regional policy issues. Sixth, it is strongly applied, using an "end-to-end" climate change research approach that includes: 1) two workshops with collaborators to improve the relevance of the scenarios and analyses and communicate the findings; 2) a novel workshop with writers and philosophers to explore the broader implications of our research to society; and 3) incorporation of our findings into U.S. Forest Service sponsored decision support software.

Michael Thompson/Iowa State University/USDA Funded
Biofuel Cropping Systems For Feedstock Production and Greenhouse Gas Mitigation

This project will help NASA and USDA understand how bioenergy cropping systems affect the global carbon cycle and identify agricultural activities that can reduce atmospheric concentrations of greenhouse gases. In the U.S. Midwest, crop production systems dominate the landscape and therefore play a critical role in the region's carbon cycle. Not only do crop production systems require carbon inputs to provide the energy for fertilizing, planting, and harvesting the crop, they determine how much terrestrial carbon can ultimately be stored for short or long periods over extensive portions of the landscape. As energy prices rise, biofuel cropping systems are likely to become increasingly prevalent in intensively farmed regions. Consequently, there is a need to identify and optimize biofuel cropping systems to provide feedstocks that effectively reduce the need for fossil fuels, while at the same time increasing soil carbon sequestration, reducing atmospheric concentrations of greenhouse gases, and minimizing water pollution.

The overall objectives of this project are to provide comprehensive, long-term comparisons and accounting of contrasting biomass feedstock production systems with respect to:

- Potential to replace fossil fuel through biomass production
- Potential to reduce greenhouse gas emissions and to increase belowground carbon storage
- Potential to reduce off-site impacts of applied fertilizers
- Potential to improve net life-cycle impacts on carbon cycling at local and regional scales

The feedstock production systems compared in a replicated field study include: continuous corn grown for grain and stover (with and without a winter cover crop), a multi-species mixture of perennial prairie plants (with and without fertilizer addition), and a conventional corn-soybean cash grain rotation for baseline comparison. Our working hypotheses are that (1) mixtures of perennial species used for biofuel feedstocks may result in greater net carbon storage and lower export of excess nutrients than corn-based feedstock production systems, and (2) cover crops such as rye will reduce net carbon and nutrient losses from corn production systems.

This project is interdisciplinary, involving specialists in bioenergy crop production, soil fertility management, greenhouse gas emissions, hydrology and water quality, soil organic matter chemistry, microbial ecology, terrestrial carbon modeling, and life-cycle analyses. Outcomes of the project include improving the predictive capacity of carbon cycle models by validation and calibration of bioenergy cropping systems, as well as support of previously developed decision-support tools for land resource managers to mitigate greenhouse gas emissions. In focusing this research effort on an integrated scientific--societal issue--bioenergy production and its environmental impacts--we will provide a comprehensive, empirical data set and modeling analyses that will be of value

both in understanding the fundamental controls on terrestrial carbon transformations in highly productive agricultural ecosystems and in predicting impacts of the widespread adoption of biofuel cropping systems on carbon cycling and the environment.

The theme of the proposed research is to explore interactions among (1) land management for agricultural production; and (2) greenhouse gas fluxes and net carbon sequestration (or loss) as a result of land use decisions. Our end-to-end study will monitor fundamental chemical, biological, and physical processes in soil and then use those observations to support end-user decision tools. By studying a range of possible biofuel production systems, we will offer new insights and alternatives concerning the tradeoffs in optimizing bioenergy production with GHG emissions and ecosystem services.

Aaron Thompson/University of Georgia/USDA Funded
Carbon Dynamics In Management Intensive Grazing Dairy Systems

SUMMARY: Increasingly, the dairy industry in the eastern US is transitioning from total confinement dairy systems (TCD) toward pasture-based, management intensive grazing dairy (MiGD) systems. This transition is driven by the fact that MiGDs require substantially less operating capital and are more economically efficient than TCD systems. Consequently, the impact of this transition and shift in land use practice on carbon dynamics may be considerable. Yet, no comprehensive C-cycle studies of this land use have been conducted in the southeastern (SE). The central goal in this proposal is to quantify changes in methane production and soil C stocks and fluxes associated with adoption of a MiGD system.

SIGNIFICANCE TO NASA/NIFA PROGRAM INTERESTS: This proposal aligns with the priorities of the NASA-USDA Carbon (C) Cycle program by addressing how an emerging land use conversion from row crop to pasture-based MiGDs in the SE U.S. will impact the C-cycle. This addresses US carbon cycle research goals (ROSES-2010, A.5-3) by: (1) providing tangible information on how regional SE C-cycling might change as a function of shifts in the dairy industry and (2) filling key knowledge gaps in how MiGDs operations affect the C-cycle that are necessary for an accurate assessment of the risk, cost, and benefits of this alternative milk production technology. In addition, this project aligns with the focus of the “Interactions between land management and land change and the carbon cycle” (ROSES-2010, A.5-4) research theme by investigating a vulnerable system with high potential for shifts in methane and soil C-sequestration fluxes. It specifically investigates the "effects of land management and land use on carbon and greenhouse gas fluxes" and considers the "tradeoffs between greenhouse gases and other products and services provided by terrestrial...ecosystems" (ROSES-2010, A.5-4). Such a land use shift would substantially increase ruminal methane emissions per hectare across the SE, but also the convertion of row cropped land to MiGD land would dramatically increase soil C sequestration rates.

OBJECTIVES: Our overall goal is to quantify the impact of MiGD's on methane emissions and soil carbon stocks. Our specific objectives are as follows: (1) To quantify enteric and field-based methane emissions as a function of MiGD forage species and

maturity. (2) To detemine the biochemical composition of manure as a function of forage species and maturity. (3) To quantify the gross carbon stock and longterm C-stabilization in MiGD fields. (4) To make regional projections of changes to soil C stock, quality, and sequestration and methane emissions associated with the projected conversion of row-crop farms to MiGD farms.

METHODS: We will accomplish our objectives by combining soil and gas sampling from a field chronosequence of MiGDs with in vitro ruminal digestion experiments of typical MiGD forages. We have established a MiGD-conversion chronosquence, with farms at 0, 3, and 6 years since conversion from row crop land use. We compliment this field approach with a laboratory-based Ruminal Digestor (simulated ruminal and hind-gut digestion) that will allow precise quantification of gas emissions and carbon compound conversion as forage plant inputs are metabolized into manure. Our Ruminal Digestor experiments will quantify (a) the flux of bovine methane emissions and (b) document changes in manure chemistry during digestion as a function of forage lignin and protein content. Our MiGD-conversion chronosequence will (a) establish changes in soil carbon stock and composition through time; and (b) evaluate gas flux and decomposition dynamics across a time-varying 13C-labeled bovine-manure amendment experiment. These lab and field results will be integrated with forage and milk production data to produce a regional estimate of C-cycle changes resulting from this expanding land use change in the SE.

Katey Walter/University of Alaska, Fairbanks/NASA Funded
Characterization of Ch4 Emissions from High Latitude Lakes in North America Using Multi-Scale Remote Sensing

Large uncertainties in the balance of natural and anthropogenic sources of atmospheric methane (CH_4), including geographic and temporal variability, should be resolved to allow policy makers to take informed action to cope with the impending societal problems of climate change. Based on extrapolation of geographically limited field studies, thermokarst (thaw) lakes, which cover up to 40% of the land in some regions, have recently been recognized as a major natural source of 14C-depleted biogenic (and sometimes geologic) CH_4. Widespread surface permafrost thaw by 2100 will subject a large fraction of the permafrost carbon pool (1672 Pg C) to methanogenesis in lake bottoms, exacerbating climate warming. This natural CH_4 source potentially overlaps the 14C-free anthropogenic source attributed to energy development and needs to be accounted for in the atmospheric CH_4 budget.

To our knowledge, no remote sensing (RS)-based data sets on northern lake CH_4 emissions exist. To constrain estimates of natural 14C-depleted CH_4 sources, we propose to develop regional, multi-scale maps of seasonal and mean annual high latitude North American lake CH_4 emissions using SAR, optical RS, and GIS modeling. This project will expand upon productive results from our predecessor NASA-funded project #NNX08AJ37G, which demonstrated that SAR backscatter data is useful in detection and quantification of CH_4 seep gas pockets trapped in lake ice. We made significant progress in understanding SAR signal interactions with CH_4 bubbles, determining sensitive SAR observation parameters, and establishing statistically significant models. Our next goals

are to: i) Automate separation of the CH4 bubble signals in SAR from other confounding signal components using a Textural Classifier Neural Network Algorithm, ii) Formulate a mathematical relationship between SAR backscatter and emitted CH_4 volume, and iii) Develop generalized spatial models for the transfer of locally established findings to regional levels.

We will also build upon recent pilot work showing the potential use of optical aerial and high-resolution satellite imagery to detect and quantify CH_4 seeps, providing cross-validation of results from SAR and field data.

In addition to biogenic CH_4 seeps, we will investigate the potential relationship between permafrost thaw and geologic (associated with underlying coal, natural gas, and potentially gas hydrates) CH_4 seeps, which are also known to occur in thermokarst lakes.

This multi-scale project will include: 1) Ground-based validation of biogenic and geologic CH_4 seeps; 2) aerial surveys of CH_4 in lake ice; 3) site-specific quantification of CH_4 seeps using SAR and optical RS; 4) regional up-scaling to produce maps of seasonal and annual lake CH_4 emissions in major North American lake districts using RS and GIS-based lake classification, new and published lake CH_4 ground data, and modeled lake-ice phenology; and 5) comparisons with NASA airborne CARVE and satellite AIRS atmospheric CH4 data.

Anticipated results include identification of hotspot regions of biogenic and geologic lake CH4 emissions associated with permafrost thaw and large pulse releases during spring ice-melt.

The RS products of this study will inform decision makers and scientists about the northern lake source in the global atmospheric CH_4 budget, provide additional ground information from northern high latitude natural lake CH_4 (and CO_2) sources for relevant current (AIRS, EV-1 CARVE) and future (OCO) NASA missions, address the National Research Council's recommendation to consider potential for abrupt release of CH_4 (from geologic CH_4 as terrestrial permafrost thaws), and meet shared objectives of NASA's Earth Science Research Program for carbon cycle science and the North American Carbon Program (NACP) for understanding and predicting changes in North American carbon pools (e.g. permafrost-stored carbon converted to CH_4 in thermokarst lakes).

Aaron Weiskittel/University of Maine/USDA Funded
Carbon Dynamics and Forest Management: A Retrospective Analysis and Projection of The Potential Effects of Land Use, Climate Change, and Natural Disturbances In Northeastern Forests

The extensive forests of the northeastern United States have been identified as one of the highest forest carbon producing areas in the country (Milbrandt, 2005), capable of producing an estimated 1.1 million dry tons of biomass annually (Perlack et al., 2005). Despite this tremendous carbon potential, there is still substantial uncertainty due to increased forest harvest intensities, altered forest management activities, vulnerability to natural disturbance like spruce budworm, and the influence of a changing climate. In particular, Maine, the most forested state in the US (90%) and has the largest contiguous block of privately-owned commercial forestland (4 million ha) in the nation, has seen drastic changes in forest carbon due to an array of factors. Some of the most important

include a change in policies that govern forest management, shift of ownership from corporation to financial investors, and the lasting effects of a severe spruce budworm outbreak in the 1980s. This has created a complex landscape that varies drastically in forest species composition and age structure. Building off of previous NASA funding, this project proposes to use an innovative and automated technique to map past forest harvest activities and characterize the current composition and age class structure using remotely sensed information. These techniques will be used to create the necessary information to initialize a spatially-dependent landscape simulation system for a representative and extensive area in Maine (4 million ha). Simulations of various alternative future scenarios will be conducted that account for the various factors that will influence carbon dynamics and system sensitivity will be assessed. In addition to carbon, the future scenarios will be assessed for their impact on biodiversity, wood fiber supply, and other landscape spatial metrics. The project will provide a robust and flexible technique for using remote sense data to inform a landscape simulation system that can be extended other regions. In particular, the project will identify the influence of forest management activities and land use change on forest carbon, which will help clarify the most effective methods for improving the forest carbon balance in the future.

Paul Wennberg/California Institute of Technology/NASA Funded
Constraining Fluxes of Carbon With Total Column Measurements of CO_2 and CH_4

The 2009 National Research Council report ("Restructuring Federal Climate Research to Meet the Challenges of Climate Change") identified the need to establish a US climate observing system to provide and maintain the data needed to address climate change. This report identified a continuing need to monitor and verify mitigation efforts and carbon treaties. Several recent studies, including a workshop held at the Keck Institute for Space Science at Caltech (http://www.kiss.caltech.edu/workshops/carbon2009/index.html), illustrated the need to improve our understanding of natural carbon exchange if such treaty verification efforts are to be successful. Understanding the natural carbon cycle is, of course, central to addressing the broad question posed by NASA's carbon cycle research program effort within the USGCRP: "How large and variable are the dynamic reservoirs and fluxes of carbon within the Earth system and how might carbon cycling change and be managed in future years, decades, and centuries?".

This proposal directly addresses two themes of the carbon cycle science call:

3. Advancing the scientific basis for space-based measurements of CO_2 and CH_4.
5. Synthetic and integrative research to advance the carbon-related goals of ongoing research activities under the USCCSP and the carbon-related goals and objectives of related national and international programs.

The proposed study includes continuation support for operation of the Total Carbon Column Observing Network (TCCON), a global network of ground-based Fourier transform spectrometers that measure column abundances of CO_2, CO, CH_4, N_2O and other molecules that absorb near infrared sunlight. With stringent requirements on the

instrumentation, data processing and calibration, the network achieves an accuracy and precision that is unprecedented for remote sensing observations (better than 0.25%). This makes the TCCON a valuable tool for further understanding the carbon cycle and validating satellite measurements.

TCCON was built with support from the NASA's Terrestrial Ecology Program and the Orbiting Carbon Observatory and has grown organically to include a large number of non-US investigators. Maintaining required quality requires, however, close collaboration of these investigators. Support is requested here to 1) continue operations of the Park Falls, Wisconsin TCCON site, 2) improve retrievals of GHGs from the TCCON spectra; 3) analyze aircraft profiles obtained over the TCCON sites to evaluate network accuracy and precision; 4) facilitate outreach and public data delivery; 4) improve coordination within the network and provide project support for all users through software development and release, and 5) enhance the inter-network communication.

We will use the TCCON observations as well as aircraft measurements of total column CO_2 (XCO_2) and CH_4 (XCH_4) to evaluate satellite measurements of the same quantities. We use these observations to investigate the regional-scale exchange of these gases between the atmosphere, the land and the ocean. Such information is required for: understanding how these fluxes may change in a changing environment; for determining the emissions of these greenhouse gases from regions or countries; for understanding the interactions of climate and the carbon cycle.

Steven Wofsy/Harvard University/NASA Funded
Source Attribution, Emission Monitoring and Treaty Verification By Combining Remote Sensing and Suborbital Data

The proposed work addresses the need to accurately measure the changes over time in emissions of the main carbon greenhouse gases (GHGs), carbon dioxide (CO_2) and methane (CH_4) from major countries or emitting regions, as part of the implementation of a future international agreement to limit GHG emissions. Global scale data for treaty monitoring will come from satellites. National emissions have a strong imprint on atmospheric concentrations, but the strongest signals reside at length scales too small and frequencies too high to be measured comprehensively from space. These signals are averaged out as ‘noise’ in current algorithms. Diurnal variations have key diagnostic information, especially for CO_2, but cannot be measured from Low Earth Orbit.
We propose a framework to add information to satellite retrievals and to the analysis of emission rates and trends, using high-resolution data obtained within source regions. We will develop a very-high-resolution model framework to ingest and assimilate in situ data, create a regional optimized surface flux product, and accurately aggregate the results to satellite-observable scales. The components of the proposed work are:
1. Develop a comprehensive, consistent, open database for key GHGs (CO_2, CH_4), and for CO (a critical ancillary molecule) from surface stations and aircraft in target regions in North and South America (population centers, wetlands, industrial regions, Amazon Basin).

2. Construct high-resolution (vertical, horizontal, temporal) full-column realizations for these gases using the Stochastic Time-Inverted Lagrangian Transport (STILT) model at observation sites in target regions. This step involves (a) computation of high-resolution assimilated meteorological fields using the WRF or BRAMS model, (b) creation of low-dimensional a priori emission models for CO_2, CH_4, and CO, coupled to WRF or BRAMS if needed, (c) running STILT to create the realizations, and (d) optimizing the emission model to best match observations. A by-product will be the regional trace gas budget.
3. Generate time/space-resolved XCO_2, XCH_4, and XCO and simulate satellite retrievals to quantitatively assess (i) the capability of the combined framework to measure means, errors, and trends of emissions, for example, by providing adaptive priors or other predictor-corrector approaches to improving the satellite products, and (ii) the information gain from the infusion of in situ data, for current and planned satellites and for hypothetical sensors that could be deployed in the next ~10 years. The results of this work will be a prototype framework for treaty verification and an assessment of the value added from such a framework. This element provides quantitative assessment of the capability of current (GOSAT), planned (OCO-2), and hypothetical follow-on satellites to contribute to treaty monitoring and verification.
4. Develop new strategies for measurements, algorithms, and data analysis to ingest information from fine-grained in situ data into satellite retrievals. High-resolution realizations from our framework provide adaptive priors for satellite algorithms linked directly to a complete regional emissions budget and in situ data; they can potentially exploit ratio measurements for GHGs relative to CO to partition emissions by sector or process, and to utilize the covariances of errors in CO, CO_2, and CH_4 to improve retrieval accuracy.
The results of this work will be a prototype framework for ingesting in situ fine-grained data into satellite retrievals, an assessment of the value added from this framework in the context of treaty monitoring and verification, an optimal link between surface emission rates, in situ data, and satellite observations, and validation of GOSAT and OCO-2 using aircraft and ground data.