The National Aeronautics and Space Administration (NASA) solicited proposals for investigations to advance the continuing prototype product development, research, and scoping of a carbon monitoring system. Congress directed NASA to allocate $10 million in Fiscal Year (FY) 2013 funding for carbon monitoring with emphasis on the acquisition, field sampling, quantification, and development of prototype Monitoring Reporting and Verification (MRV) system capabilities which can provide transparent data products achieving levels of precision and accuracy required by current carbon trading protocols. The use of commercial off-the-shelf technologies was recommended. NASA also was directed to make up to 20 percent of NASA’s 2013 CMS funds available for international REDD projects.

Proposals for the following types of prototyping, research, and scoping activities for carbon monitoring were requested:

- Studies using commercial off-the-shelf technologies to produce and evaluate prototype MRV system approaches and/or calibration and validation data sets for future NASA missions;
- Studies that conduct MRV-related work in support of international REDD or REDD+ projects;
- Studies that address research needs to advance remote sensing-based approaches to MRV (e.g., quantification of forest degradation; independent assessment of the accuracy of airborne remote sensing observations of biomass and carbon stocks; use of airborne flux observations as an alternative method for quantifying net carbon emissions/storage);
- Studies to improve the characterization and quantification of errors and uncertainties in existing and/or proposed NASA CMS products, including errors and uncertainties in the algorithms, models, and associated methodologies utilized in creating them; and
- Studies of stakeholder interests and requirements that offer to 1) understand and engage the user community for carbon monitoring products and/or 2) evaluate current and planned NASA CMS products with regard to their value for decision making by these users.

A total of 37 proposals was received, and 17 have been selected for funding. The total funding to be provided for these investigations is approximately $19.1 million over 3 years. For Fiscal Year 2013 funds, $8.1 million is allocated to these selected investigations and $1.9 million has already been allocated to existing commitments from prior CMS solicitations. Approximately $2.6 million of the Fiscal Year 2013 funds allocated to this selection are for international REDD projects.

The investigations selected are listed below. The Principal Investigator, institution, and investigation title are provided.
This proposal provides a scope of work for studying and engaging with the user community for the NASA Carbon Monitoring System (CMS) pilot projects. Under the CMS initiative, NASA will be developing end-to-end expertise on regional, national and international carbon monitoring products based on satellite remote sensing. In this proposal, we focus on understanding and engaging the science and user community of these products to enable improved characterization of CMS products, preparation for eventual data delivery, and evaluate the CMS products that have been developed. The focus of this activity is to evaluate current and planned NASA CMS products with regard to their use in specific decision making contexts. This effort is aligned with the mission of the Carbon Cycle Science program to leverage NASA investments to discover and demonstrate applications that inform resource management, policy development, and decision making within operational agencies responsible for resource management and policy decisions that affect carbon emissions, sequestration, and fluxes among terrestrial, aquatic, and atmospheric environments. Our proposed research is highly relevant to the following activities listed as a priority for this NRA: Studies of stakeholder interests and requirements that offer to 1) understand and engage the user community for carbon monitoring products and/or 2) evaluate current and planned NASA CMS products with regard to their value for decision making by these users. The effort is designed to identify and engage with the user community for carbon monitoring products and to ensure that every scientist working within CMS has exposure to these users. Determining the requirements of the broader decision making community is a critical element of an effective applications program. We will work to find policy and practical users of CMS products for the atmosphere, ocean, and land. We will express the needs of the community to the CMS SDT and the broader CMS science community to help guide product development. Thus, we will develop a path that illustrates the connection between the user needs, the CMS product and the decision and policy frameworks that link the science to society. In order to foster this interplay between science capabilities and user needs via CMS product development and product application in decision-making environments, we have three broad objectives:

1) Develop communication strategies that link directly to the goals, objectives and accomplishments of the NASA CMS program and build a broad support system for CMS science PIs through transparent and inclusive processes involving scientists and end users;

2) Identify group(s) of institutions and organizations who become "early adopters" of NASA CMS products. Selected early adopters will have an immediate use for the CMS product(s) and have clearly identified requirements for existing and planned NASA CMS scientific output; and

3) Evaluate the current and planned NASA CMS products, and determine the degree to which this proposed CMS Applications program has met success criteria.
Project Summary: Because of episodic uncontrolled fires within drained peat-swamp forests, Indonesia is ranked the 4th largest CO2 emitter over the last half century. The former 1 million hectare Mega Rice Project (MRP), designed to convert extensive peat lands into farm lands, is a major emissions source. Deep organic soils storing vast amounts of carbon are now being lost to decomposition and combustion. The 120,000 ha Kalimantan Forests and Climate Partnership (KFCP) Reduced Emissions from Deforestation and forest Degradation (REDD+) project is within the former MRP. In collaboration with the Indonesian government's Forestry Research and Development Agency (FORDA), we will develop a prototype peat-fire emissions module for KFCP to incorporate into the Indonesian National Carbon Accounting System (INCAS). This capacity will enable annual quantification of fire-related emissions. Our research project will utilize Landsat and MODIS data and products to quantify land cover changes, burned area and estimate the timing of fire activity. We will incorporate TRMM data for relating precipitation history to the timing of observed water table changes that impact peat-fire activity at KFCP. We will integrate satellite data with existing aerial KFCP Lidar (2007 & 2010), and propose a repeat Lidar collection during the study to provide quantified temporal topographic change maps to validate our modeled results of fire-related peat consumption. This project will leverage the extensive and ongoing data collection efforts for hydrology, fuels, land uses and fire occurrence at KFCP, with our initial field work and laboratory testing of regional peat combustion and emission characteristics to provide guided field testing of background and fire-related carbon emission rates and types (e.g. methane, CO2, CO, particulates, other) during El Nino and non-El Nino years as available. Through groundbreaking emissions field sampling of in-situ smoldering surface, shallow (<20 cm) and deep (>20 cm) peat fires, with on-site gas chromatography for quantifying reactive species, whole air sampling for precise lab measurements of non-reactive gases, and simultaneous filter sampling of particulates, we will create comprehensive and pertinent emissions factors (EFs) that will be critically important for assessing the health impacts and total global warming potential (GWP) of these emissions. In our interdisciplinary research, we will investigate the chains of social and bio-physical events leading to these deep-peat fires, integrating fire scene analyses with social data to describe when, where, how, and under what conditions fires within KFCP have occurred, so that more effective mitigation strategies can be developed in the future. Accurate accounting of peat-fire carbon emissions requires understanding how their presence, depth of burning, and spread rates relate to the interplay of climate, weather, land use, land cover, drainage status, disturbance history, fire type, peat depth and composition. Modeling this phenomenon requires defining 1) the annual surface area burned, 2) the available fuel fraction (burnable) at each location through time, and 3) the amount of fuel consumed per unit area. We will implement a modeling approach that initially uses existing data on the peat hydrology, climate, land cover, burned area, timing of ignitions and fuel loads to stochastically provide peat fire probability and parameterize
depth and area burned from the 2007 Lidar data. This initial model will be used to project
the expected area, type, and depth of burning from 2007-2011 and then checked against
the 2011 Lidar data set to refine calibration of the modeled parameters. The third
modeling phase will provide Monte Carlo estimates of type, depth and area of burning,
with emissions quantitatively weighted by appropriate EFs derived for surface, shallow
and deep peat smoke amounts that will be validated using the proposed third Lidar data
collection.

Warren Cohen/USDA Forest Service
An Historically Consistent and Broadly Applicable MRV System Based on Lidar
Sampling and Landsat Time-Series (Tested in the US, and applied to the US
NGHGI reporting system)

We focus our attention on the development of a Monitoring, Reporting, and Verification
(MRV) accounting system that could be used by developing countries within the context
of the United Nations (UN) REDD Programme. Because one system will not fit all needs,
we consider different biomass estimation frameworks and different components for
inclusion in the system. Design-based inference is commonly applied to a sample field
plot network, as it is for the US National Greenhouse Gas Inventory (NGHGI) baseline
reporting to the UN Framework Convention on Climate Change (UNFCCC). But field
plot networks are expensive to install and maintain. Sampling with lidar strips, supported
by a smaller set of plots may be an attractive alternative that is highly relevant to many
REDD countries, as is the use of Landsat for disturbance monitoring. Biomass estimation
uncertainties associated with use of these different datasets in a design-based inference
framework will be examined. We will also develop and test estimators that rely primarily
on Landsat data within a model-based inference framework. The contributions from
Landsat are the current (e.g., 2013) spectral response and metrics that describe
disturbance history derived from a time series leading up to the current date. In this
context, either plot data or lidar data can be used to parameterize the model and we will
contrast the uncertainty effects of these datasets.

A key advantage of the model-based framework is that it can be extended back in time
(e.g., to 1990) using a consistent approach. The main feature of the model-based
approach is that it relies directly on disturbance history as an indicator of biomass
density. Using Landsat spectral data from a given date (e.g., 2000) and disturbance
history metrics derived from a time series leading up to that date (e.g., 1984-2000), the
statistical model developed for the current period (e.g., 2013) can be applied historically.
This is critical because REDD requires a way to estimate biomass historically, back to a
baseline year of 1990. For the approach to take maximum advantage of disturbance
history metrics to predict biomass density, a sufficient time series length is critical. This
requires that we reach back into the MSS archive to develop the disturbance history
metrics for the approach to be fully effective in estimating biomass for the 1990 baseline.

The US, while not a REDD country, is a party to the UNFCCC and has a need for similar
NGHGI baseline information. The various components of our MRV system will be tested
in the US, where the best data are available for parsing the uncertainty contributions of
the several system components we will test. In doing so, we will develop and test an historical biomass mapping approach that, if implemented, would provide REDD countries a practical set of workflows for integrated monitoring of current and historic baseline carbon stocks and trends, with an understanding of the uncertainties associated with different components of the alternative workflows. Additionally, with the improvements expected from including Landsat-derived disturbance history into the methods used for the US NGHGI, this research would provide NASA and CMS with a collaborative roll in the process of reporting US forest carbon estimates to the UNFCCC.

George Collatz/NASA GSFC

Improving and Extending CMS Land Surface Carbon Flux Products Including Estimates of Uncertainties in Fluxes and Biomass

This proposal addresses the Studies to improve the characterization and quantification of errors and uncertainties in existing and/or proposed NASA CMS products, including errors and uncertainties in the algorithms, models, and associated methodologies utilized in creating them; component of CMS call for proposals. Our team was originally funded in Phase I of the CMS project to provide land surface carbon fluxes (NPP/GPP, RH/RE, Fire from CASA-GFED3) for the period 2009-2010. We produced these products, evaluated them against other models and contributed to the interpretation of modeled atmospheric CO2 distributions produced by GSFC’s GEOS-5 transport model and the source/sink distributions produced by JPL’s atmospheric inverse model. Our data products are available on the CMS website. For Phase II, we did not seek funding support but contributed to the Pawson and Bowman projects as collaborators providing fluxes for 2011 and further evaluation of those. Our data products are well suited for use by other CMS projects because they are highly constrained by satellite observations and have a long history of evaluation by the atmospheric CO2 modeling community. There is the need for continued updates of these key land data products and for estimates of uncertainties which were not previously supplied.

For this proposed work we plan to produce land carbon fluxes for 2012 from CASA-GFED3 by the end of this calendar year. In subsequent years of the proposal we will introduce the new updated version of the model (CASA-GFED4) with improved physiological and fire parameterizations, improved burned area estimates including representation of smaller fires, and finer spatial resolution (1/4 degree) extending the time series into the future with a latency of ~5 months. We have begun preliminary uncertainty analyses of the CASA-GFED3 fluxes by first testing the sensitivity of the modeled fluxes to characteristic model parameters. From the sensitivity analyses we are selecting a number of key parameters and using published and expert opinion estimates of uncertainties in these parameters to estimate flux uncertainties using a Monte Carlo method. We will estimate uncertainties in the individual fluxes (NPP, RH, fires, NBP, GPP, RE) at monthly time steps for the entire period of the data set. Quantified flux uncertainties are critically needed by the CMS atmospheric modeling groups for their estimates of overall uncertainties in surface carbon sources and sinks. Our simulations also produce global biomass estimates at the model’s native resolution with uncertainties. We plan to evaluate these estimates against others including the CMS Biomass products.
National and international programs have an increasing need for precise and accurate estimates of forest carbon and structure to support greenhouse gas reduction plans, climate initiatives, and other international climate treaty frameworks such as REDD++. Central to these activities is the development of MRV (measurement, reporting and verification) systems that provide an accounting of forest carbon emission and sequestration at high spatial resolution with appropriate temporal frequencies. Such systems can be used to support and sustain the development of an "ecomarket" infrastructure centered on carbon, along with other ecosystem services, such as biodiversity, water resources, and the like. Central to ecomarkets is the creation of financial incentives that reward the preservation and enhancement of ecosystem services through time, as enabled from robust MRV systems.

NASA has recognized the urgent need for the development of MRV through its initiation of the Carbon Monitoring System (CMS) program. The University of Maryland, working with NASA centers, the USFS, and commercial entities has led research efforts in Phase I and Phase II that have laid the basic groundwork for MRV. Our Phase II project uses existing, wall-to-wall airborne lidar coverage and in-situ field data collection to produce high-resolution maps of carbon stocks for all of Maryland. These same data are also used to drive a prognostic ecosystem model to predict carbon fluxes and carbon sequestration potential. This work has demonstrated the feasibility of large-scale mapping using airborne lidar, an important first step, and suggests logical follow-on activities that should be undertaken towards the realization of operational MRV systems that are responsive to local, national and international interests in management and policy.

The overall goal of this project is the continuing development of a prototype MRV system based on commercial off-the-shelf (COTS) remote sensing and analysis capabilities to support ecomarket infrastructure in Sonoma County, California. Building on our East Coast county-level work as part of CMS I and CMS II, we seek to address the following questions:

- What accuracies are achievable using predominantly COTS-based approaches to high-resolution MRV for forest carbon?
- What is the "price-of-precision" for MRV systems and how does this vary as a function of sample design, ground data, remote sensing data acquisition and analysis costs?
- How can stakeholder needs and requirements be integrated during the creation and implementation of MRV systems to provide effective decision support and compliance capabilities, and with better-informed policy decisions? Can a cloud-based architecture be used to facilitate the initiation and use of MRV systems to enable their implementation domestically and abroad?

We have identified five objectives to answer our research questions: (1) Integration of Sonoma County stakeholder needs and requirements into the MRV system design. (2) High-resolution wall-to-wall estimation of carbon stocks and their uncertainties for Sonoma County and mapping of sequestration potential under various development
scenarios using the Ecosystem Demography model. (3) Development of the key components of an end-to-end MRV system that includes data acquisition, warehousing, baseline quantification, data accessibility, accounting, reporting and stakeholder communication. (4) Analysis of the "price-of-precision" through a cost-benefit analysis of data resolution relative to accuracy achievable at particular spatial scales e.g. United Nations Framework Conference on Climate Change (UNFCCC) Tier 1 vs. Tier 3. (5) Demonstration of a functional prototype MRV platform with visualization, and analytical capabilities for addressing Sonoma County initiatives. Our basic approach to high-resolution carbon stock mapping has been established in our CMS Phase 1 (two Maryland counties) and Phase 2 (23 Maryland counties) efforts.

**Manvendra Dubey/Los Alamos National Labortaory**

**Off-the-shelf Commercial Compact Solar FTS for CO2 and CH4 Observations for MRV**

Monitoring, reporting and verification (MRV) of natural sources and sinks and anthropogenic emission of carbon dioxide (CO2) and methane (CH4) are crucial to predict climate change and develop transparent accounting policies to contain climate forcing. Remote sensing technologies are beginning to monitor CO2 and CH4 from ground and space using high-resolution solar spectroscopy enabling direct MRV. However, the current ground based coverage is very sparse due the need for large and expensive high-resolution spectrometers that limits our MRV abilities, both regionally and globally. There are striking monitoring gaps in Asia (China and India), South America and Africa where the CO2 emissions are growing and there is a large uncertainty in fluxes from land use change and biomass burning. Our project will evaluate the precision, accuracy and stability of new off-the-shelf commercial, compact, affordable and easy to use low-resolution spectrometers by comparing with the much larger high-resolution spectrometers used to monitor CO2 and CH4. While initial results are promising our study will encompass real world conditions and challenges. If we are successful the new off-the-shelf spectrometers will dramatically expand the coverage of regional column CO2 and CH4 observations, particularly in gap regions in the developing world. This will enable transparent and reliable MRV that would put carbon cycle science and carbon trading and put climate treaty verification on a firm foundation.

**Riley Duren/Jet Propulsion Laboratory**

**Understanding User Needs for Carbon Monitoring Information**

The objectives of the proposed work are to: 1) engage the user community and identify needs for policy-relevant carbon monitoring information, 2) evaluate current and planned NASA Carbon Monitoring System data products with regard to their value for decision making, and 3) explore alternative methods for visualizing and communicating carbon monitoring information and associated uncertainties to decision makers and other stakeholders.

We will establish a framework that facilitates frequent and sustained engagement of carbon policy and management stakeholders to define requirements for CMS data
products. Our team will work with the CMS science team to acquire prototype data products and help stakeholders evaluate the utility and relevance for policy planning and decision support. We will develop a Carbon Calculator and Data Portal that integrates multiple CMS products to enable those evaluation efforts. Where necessary we will explore new approaches for presenting the results of CMS data products and their uncertainties to decision-makers, again with the intent of helping to inform future CMS requirements and improve relevance of the ultimate data products.

Our team combines experts in carbon management and policy from a representative cross-section of stakeholders in the US government (including the State Department's Bureau of Oceans and International Environment and Scientific Affairs (OES), the Environmental Protection Agency (EPA), and the White House Council on Environmental Quality (CEQ) with other experts working at the interface of science and policy for carbon monitoring (co-investigators from JPL, RFF, ASU, and USFS). The team will meet regularly and share information through a flexible web portal that leverages emerging tools for visualizing data.

We will apply the above process to study a range of representative policy scenarios. Examples of topics that may be explored include but are not limited to: policies and management efforts focused on: 1) Land Use, Land Use Change, and Forestry (LULUCF) fluxes for the United States and/or selected developing countries (e.g., Indonesia), 2) Forest carbon stocks and disturbances for the US and/or tropical countries or sub-national projects therein, 3) methane (CH4) emissions from major shale gas basins in the US, and 4) fossil fuel CO2 and CH4 emissions from cities and industrialized states and provinces (including potential linked sub-national carbon emissions trading systems).

Heather Graven/
Quantifying Fossil and Biospheric CO2 Fluxes in California Using Ground-Based and Satellite Observations

This proposal develops a prototype system that combines commercial ground-based measurement techniques with satellite data to address Monitoring, Reporting and Verification (MRV) of regional CO2 fluxes from fossil fuel emissions and biospheric exchange. The system will be centered on the State of California, where it will be responsive to the State's policy measure to reduce greenhouse gas emissions, California's Global Warming Solutions Act (AB-32) which includes a cap-and-trade program, and where a relatively dense measurement network for atmospheric CO2 concentration is already in place. We will use this existing network to conduct field sampling for the measurement of radiocarbon content (D14C) in atmospheric CO2 that will enable us to identify fossil-derived and biospheric-derived CO2 [Turnbull et al. 2006; Graven et al. 2009] at 9 sites across the state. The D14C-based observations of fossil-derived and biospheric-derived CO2, along with measurements of total CO2 concentration from ground-based and satellite platforms, will be analyzed in an atmospheric inversion framework that we will develop from a similar framework currently being used to estimate emissions of CH4 in California [Jeong et al. 2012; Fischer et al. 2012].
Unique contributions of the proposed work involve the integration of D14C data into an inversion framework to optimize fossil fuel emissions explicitly, and the integration of satellite-derived total column CO2 with ground-based data. The proposed work will also provide evaluation of the natural sink or source of CO2 in California's terrestrial biosphere and evaluation of the biospheric models, CASA-GFED and NASA-CASA, across the widely varying biome types and land uses present in California. These models incorporate satellite retrievals of vegetation index and land cover and are currently used in the NASA Carbon Monitoring System Flux Product.

Data products resulting from the proposed work include optimized CO2 flux distributions and totals, including uncertainty, for the State of California for both fossil fuel emissions and biospheric exchange, providing an atmospheric observation-based MRV product that can be used to support California's AB-32 policy. The prototype system we develop could be replicated in other regions, providing similar MRV applications to other greenhouse gas emission policies.

References


Stephen Hagen/Applied Geosolutions, LLC
Operational Multi-Sensor Design for National Scale Forest Carbon Monitoring to Support REDD+ MRV Systems

Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have been requested to establish robust and transparent national forest monitoring systems (NFMS) that use a combination of remote sensing and ground-based forest carbon inventory approaches to estimate anthropogenic forest-related greenhouse gas emissions and removals, reducing uncertainties as far as possible. A country's NFMS should also be used for data collection to inform the assessment of national or subnational forest reference emission levels and/or forest reference levels (RELs/RLs). In this way, the NFMS forms the link between historical assessments and current/future assessments, enabling consistency in the data and information to support the implementation of REDD+ activities in countries. The creation of a reliable, transparent, and comprehensive
NFMS is currently limited by a dearth of relevant data that are accurate, low-cost, and spatially resolved at subnational scales.

We propose to develop, evaluate, and validate several critical components of a NFMS in Kalimantan, Indonesia, focusing on the use of LiDAR and radar imagery for improved carbon stock and forest degradation information. Our goal will be to evaluate sensor and platform tradeoffs systematically against in situ investments, as well as provide detailed tracking and characterization of uncertainty in a cost-benefit framework. Kalimantan is an ideal area to evaluate the use of remote sensing methods because measuring forest carbon stocks and their human caused changes with a high degree of certainty in areas of dense tropical forests has proven to be difficult. While the proposed NFMS components will be developed at the subnational scale for Kalimantan, we will target these methods for applicability across broader geographies and for implementation at various scales.

This proposed research will advance the state of the art of Measuring, Reporting, and Verification (MRV) system methodologies in ways that are both technical and operational. First, because a primary focus of carbon monitoring systems, especially in developing countries, is on cost-effectiveness, our analysis of optimal inputs of information from various satellite, airborne, and in situ measurements will provide valuable practical information that countries can use to consider the tradeoffs. Second, because quantifying and understanding uncertainty is critical both in an Earth science research context and with regard to payment for ecosystem services, our development of reusable methods for tracking and evaluating uncertainty within a carbon monitoring system will provide a framework for stakeholders and researchers to understand and minimize errors across MRV components. Third, because carbon monitoring requires integration of advanced technologies with multidisciplinary scientific methods from forestry, ecology, soil science, remote sensing and biogeochemistry, our team's expertise is particularly well-constructed to address these complex scientific and technical issues.

Michael Keller/ USDA Forest Service
A Data Assimilation Approach to Quantify Uncertainty for Estimates of Biomass Stocks and Changes in Amazon Forests

Brazilian tropical forests contain approximately one-third of the global carbon stock in above-ground tropical forest biomass. Deforestation has cleared about 15% of the extensive forest on the Brazilian Amazon frontier. Logging, and understory forest fires may have degraded a similar area of forest. In response to the potential climatic effects of deforestation, policy makers have suggested reductions in emissions through deforestation and forest degradation and enhanced forest carbon stocks (REDD+). Carbon accounting for REDD+ requires knowledge of deforestation, degradation, and associated changes in forest carbon stocks. Degradation is more difficult to detect than deforestation so SilvaCarbon, an US inter-agency effort, has set a priority to better characterize forest degradation effects on carbon loss.

We propose to quantify carbon stocks and changes and associated uncertainties in Paragominas, a jurisdiction in the eastern Brazilian Amazon with a high proportion of
logged and burned degraded forests where political change has opened the way for REDD+. We will build on a long history of research including our extensive studies of logging damage. In addition, we will use recent forest inventories and airborne lidar supported by USAID and managed by the US Forest Service and the Brazilian Corporation for Agricultural Research (EMBRAPA) under the Sustainable Landscapes Brazil program. Existing data will allow us to start analysis immediately and will also permit REDD+ relevant multi-temporal measurements of change during the brief three-year study period.

We plan to supplement the existing data by collection of additional ground-based forest inventory data contemporary with commercial airborne lidar (supported by USAID) and Landsat remote sensing data that will incorporate a novel use of time series data to estimate the structural properties of degraded forests using bidirectional reflectance information. We identify two objectives for forest carbon accounting at the jurisdictional level:

- Quantify spatially explicit above-ground carbon stocks and the changes in carbon stocks;
- Quantify spatially explicit uncertainties in above-ground carbon stocks and changes in carbon stocks

We will meet these objectives by employing innovative data assimilation methods. Our approach employs a hierarchical Bayesian modeling (HBM) framework where the assimilation of information from multiple sources is accomplished using a change of support (COS) technique. The COS problem formulation allows data from several spatial resolutions to be assimilated into an intermediate resolution. This approach provides a mechanism to assimilate information from multiple sources to produce spatially-explicit maps of carbon stocks and changes with corresponding spatially explicit maps of uncertainty. Importantly, this approach also provides a mechanism that can be used to assess the value of information from specific data products. Hence future data collection can be optimized in the context of the reduction of uncertainty. The spatially explicit quantification of uncertainties naturally provides insights into effective sampling designs. Members of the team used this statistical approach previously as part of prototyping efforts for the National Ecological Observatory Network.

The proposed work will add a new research dimension to the Sustainable Landscapes Brazil program, a direct outcome of the US-Brazil Memorandum of Understanding on climate change. Through that program, we have already successfully acquired airborne remote sensing data in Brazil and all requirements for international data collection have already been met. Because the proposed research is closely linked to an active program of international cooperation and capacity building, we will be in a unique position to transfer the results of our research to practitioners in the Brazilian government and in Brazilian civil society.
We propose to support the development and improvement of national MRV systems for REDD+ through two objectives. First, we will develop, test, and share with the public domain robust and transparent methods for mapping activity data (e.g., deforestation, forest degradation). Second, we will conduct an uncertainty analysis of carbon emission estimates from the activity data and from emission factors. We will use novel approaches to time series data mining of optical and radar satellite imagery and conduct the work in three test sites (Colombia, Peru and Mexico) identified as National Demonstrator sites by the Group on Earth Observation's (GEO) Forest Carbon Tracking Task (GEO-FCT). The test sites include a variety of ecosystems, biomass regimes, and cloud-cover conditions, and they exhibit a range of drivers of deforestation and land conversion methods, including selective logging, burning, clearing for permanent conversion, and forest regrowth. A large amount of data from optical and radar satellites has already been collected for these GEO-FCT verification sites.

More specifically, we will develop an algorithm from optical and radar time series fusion to produce an accurate assessment of annual changes in areas experiencing deforestation, forest degradation, and forest regrowth (i.e., activity data). The work will include an approach for distinguishing between natural disturbances and permanent anthropogenic change. We will assess the uncertainty and accuracy of the activity data estimated with this algorithm.

To assess the uncertainty of carbon emission estimates, we propose to compile a database of country specific emission factors, stratified by land-cover categories (from the first objective), and linked with carbon density estimates from forest inventory and existing biomass maps. The database will contain uncertainty estimates. To provide guidance for national MRV implementation, we will also explore the impact of uncertainties in activity data and emissions factors on carbon fluxes estimated using a bookkeeping model.

The proposed work is relevant to the specific objectives of this NASA Carbon Monitoring System solicitation, including rigorous exploitation of NASA and international partner satellite remote sensing resources and computational capabilities. The Subsidiary Body of Scientific and Technological Advice (SBSTA) of the UNFCCC agreed in June 2013 that continuous improvement of data and methods is vital for developing MRV systems for REDD+. In particular, SBSTA identified the need to reduce uncertainties in emissions accounting and to develop methodologically consistent ways to harness new observational data, whether field or remote sensing, that can be used to report against reference levels of deforestation and forest degradation, as well as associated reference emission levels (SBSTA, 2013). To develop methodologically consistent, transparent, yet flexible accounting methods, as required in the international framework of the UNFCCC, as well as numerous bi- and multi-lateral agreements, the
Group on Earth Observation (GEO) has established a Forest Carbon Tracking Task (GEO-FCT). PI Kellndorfer and Co-I’s Woodcock and Olofsson are among those chosen by GEO to formulate and support the implementation of a Global Forest Observing Initiative (http://geo-fct.org). Support of this proposal would allow them to carry out that work.

Thomas Lauvaux/The Pennsylvania State University
Quantification of the Sensitivity of NASA CMS Flux Inversions to Uncertainty in Atmospheric Transport

Uncertainty in atmospheric transport and a lack of atmospheric carbon dioxide (CO2) observations are the two major sources of uncertainty in inverse estimates of CO2 sources and sinks. Space-based measurements of atmospheric CO2 will greatly increase the density of atmospheric measurements. Atmospheric transport, however, remains a major challenge. We propose to improve our understanding of the uncertainties associated with atmospheric transport in the NASA Carbon Monitoring System Flux estimation and attribution pilot project (CMS Flux). This project will focus on uncertainties at the regional to continental scale, focusing in particular on North America for calendar year 2010. The results should be applicable to any mid-latitude continental region.

We will: 1) assess the transport error in the global NASA CMS-Flux system and the mesoscale WRF-LPDM using meteorological data and CO2 profiles from airborne measurements over North America; 2) represent transport error with a physics-based ensemble of atmospheric transport configurations; and 3) estimate the contribution of transport uncertainty over North America to North American and global flux uncertainty. This proposal will address the request in the NASA CMS announcement of opportunity for, "Studies to improve the characterization and quantification of errors and uncertainties in existing and/or proposed NASA CMS products, including errors and uncertainties in the algorithms, models, and associated methodologies utilized in creating them."

We will evaluate the impact of atmospheric transport on the CMS Flux pilot products by embedding the Penn State regional atmospheric inversion system, which utilizes the mesoscale Weather Research and Forecast model (WRF), within the CMS Flux system, by simulating atmospheric CO2 and solving for continental fluxes with both systems, and by evaluating transport uncertainty by comparing the CMS Flux system output to meteorological observations and aircraft CO2 profile data.

The first objective will be met by simulating the atmospheric distribution of CO2 across North America with both WRF and Geos-Chem (the CMS Flux atmospheric transport scheme). Both simulations will use the same lateral boundary conditions and surface fluxes. Meteorological observations will be used to quantify the atmospheric transport uncertainty in CMS Flux. Aircraft CO2 profiles will be used to quantify the model-data mismatch error used in CMS Flux inversions.

The second objective will be met by running a physics-based ensemble of WRF simulations conditioned to match the range of transport errors found in the CMS Flux system by comparison to meteorological observations. This ensemble will be sampled to simulated GOSAT and OCO-2 observational patterns. This produces a set of column CO2 pseudo-data with a distribution similar to the CMS Flux transport error.
The third objective will be addressed by using this ensemble of simulated satellite observations to infer an ensemble of fluxes using the CMS Flux system. The differences among the inferred fluxes should be a realistic representation of atmospheric transport error in the CMS Flux biogenic flux product.

Thomas Nehrkorn/AER, Inc.
Prototype Monitoring, Reporting and Verification System for the Regional Scale: The Boston-DC Corridor

The world's population growth is increasingly concentrated in urban areas and this trend is expected to continue in the future. Urbanization has a profound impact on carbon dynamics, leading to increases in anthropogenic carbon dioxide (CO2) emissions and decreases in biogenic fluxes from these areas. The latter are a key component of a carbon monitoring system (CMS), while spatially and temporally resolved estimates of anthropogenic fluxes are central to meeting greenhouse gas emissions reductions goals. We intend to design a measurement network and develop an accompanying atmospheric modeling framework for downscaling the current NASA CMS flux products to the regional and local scales pertinent to Monitoring, Reporting, and Verification (MRV).

Our proposed research will focus on the Boston-DC megalopolis corridor, where about 17% of the U.S. population lives on less than 2% of the nation's land area, making it a key source of US anthropogenic CO2 emissions. Simultaneously, these urban areas are interspersed with vegetation that imposes a strong biogenic signal on the atmospheric CO2 mixing ratios.

The proposed research will proceed along three main lines: 1) High-resolution transport modeling (WRF-STILT) customized and verified for the region, 2) High-resolution CO2 flux model incorporating anthropogenic emissions estimates and the CASA model (including its 0.5-deg resolution variant that provides the foundational biosphere model for the current CMS Flux Product and nested higher resolution runs to represent the scale sensitivity within heterogeneous urban areas), and 3) Inverse CO2 flux estimates corresponding to in-situ and remote CO2 observations in and around Boston, New York City, and Washington DC. As part of the proposed work, we will quantify errors in the WRF-STILT simulations of the planetary boundary layer (PBL), relying for this purpose on remotely sensed PBL measurements by the Sigma Space Corporation's Micro Pulse LiDAR (MPL). The PBL height is a key parameter entering inverse flux estimates, as it determines the mixing region and varies inversely to the trace gas concentrations. A key result of the proposed research will be the quantification of observing requirements for flux uncertainty reduction to levels needed for MRV.

Our proposal addresses two stated goals of the NNH13ZDA001N-CMS solicitation:
- "studies using commercial off-the-shelf technologies to produce and evaluate prototype MRV system approaches"
- "studies to and quantification of errors and uncertainties in existing and/or proposed NASA CMS products, including errors and uncertainties in the algorithms, models, and associated methodologies utilized in creating them."

The proposed work will be carried out as part of the current CMS projects led by Drs. Arlyn Andrews and Steven Pawson, with which the lead proposing team at Atmospheric and Environmental Research (AER) is intimately involved, and the CMS pilot surface carbon fluxes modeling analysis.
Monitoring U.S. forest carbon stocks is critical for natural resource management and national greenhouse gas reporting activities. The USFS Forest Inventory and Analysis (FIA) program—a network of permanent forest inventory plots in the world—covers most U.S. forestlands. However, more than 450,000 km² of forests in interior Alaska (15% of US forestland) are not included in the FIA program, as these remote regions are difficult and expensive to monitor with standard field methods. Recent and projected future impacts from climate change on forest carbon stocks, composition, and extent have elevated the need to develop new approaches for forest monitoring in Alaska. In particular, airborne remote sensing offers unique advantages for monitoring remote forested regions. In many respects, the methods, logistics, and timeliness of carbon monitoring in Alaska are analogous to ongoing efforts to develop carbon monitoring systems for remote tropical forest regions to Reduce Emissions from Deforestation and forest Degradation and enhancing forest carbon stocks (REDD+).

Here, we propose to develop the first regional estimates of forest carbon stocks for the Tanana Inventory Unit of interior Alaska (146,000 km²). The proposed research leverages a sizable investment ($800k) by the USFS FIA Program in 2014 for new forest inventory plots and airborne data collection with Goddard's LiDAR, Hyperspectral, and Thermal Airborne Imager (G-LiHT; http://gliht.gsfc.nasa.gov). G LiHT is a well-calibrated airborne remote sensing package that is assembled from commercial off-the-shelf (COTS) instruments and a proven track record of timely, free, and open access to both low- and high-level products. The USFS project, a pilot study for LiDAR-assisted forest inventory in interior Alaska, does not provide support for research collaboration between NASA and USFS scientists, data analysis, or methods development. In this project, we will expand the Tanana research activity to 1) collaborate on the experimental design for optimal integration of field and LiDAR data for forest carbon monitoring; 2) compare established model-based and model-assisted methods for estimating forest carbon stocks using both plot and LiDAR information; 3) enhance the inventory activity using individual tree, species composition, and vegetation cover information from the combination of G-LiHT hyperspectral, thermal, and LiDAR sensors; and 4) characterize the impacts of recent fires and risk of future fire-driven carbon losses using the systematic sample of G-LiHT flight lines over ~2.5% of the Tanana region (3800 km²); and 5) develop new, spatially explicit estimates of carbon stocks and uncertainties using Bayesian statistical methods. The main outcomes from this work will be estimates of forest carbon stocks and associated uncertainties for the Tanana Inventory Unit. These estimates provide critical and timely information for resource management, and baseline conditions for the spatial distribution of forest cover and carbon stocks in a region that is rapidly changing from climate warming.
The research described in this proposal will develop statistically rigorous sampling design and analysis protocols that will reduce uncertainty of key estimates of target parameters of a carbon monitoring system (CMS) and lead to better quantification of uncertainty. The IPCC Good Practice Guidance emphasizes the importance of land area to estimates of carbon stocks and emissions and removals of greenhouse gases associated with land use, land-use change and forestry activities. Effective regional, national and global carbon monitoring systems can exploit satellite remote sensing in a variety of ways to substantially reduce the uncertainty of area estimates and to reduce costs associated with field sampling. A central theme of the proposed research is to develop and evaluate methods for advantageously combining remote sensing and ground data obtained from multiple sources to obtain more accurate (i.e., unbiased) and more precise estimates of land area and other key parameters of a CMS. Sampling is a key component of a CMS because much of the information needed for monitoring can only be collected in a cost-effective way via a sample. The proposed research is heavily focused on sampling methods. The outcome of the research will be recommendations for choosing a sampling design and estimation protocol that effectively combines information from multiple data sources emphasizing airborne and satellite remote sensing and field plot data. The specific objectives addressed include: 1) identify effective sampling designs and estimators that take advantage of remote sensing information to reduce costs and uncertainty associated with sample-based estimates; 2) compare different sample-based estimators proposed for a commonly used design in monitoring (two-stage cluster sampling) and provide a recommendation for which estimator(s) most effectively use remote sensing information to reduce uncertainty; 3) develop methods for quantifying measurement error (in particular, reference data error) associated with accuracy of land cover and land change maps and for estimating land cover or land change area taking into account this measurement error; 4) develop rigorous sampling design and estimation protocols for incorporating community based monitoring and volunteered geographic information into land change monitoring protocols; and 5) investigate approaches for combining information from two probability samples to improve precision of estimates. Two obvious desirable goals for designing a CMS are to reduce uncertainties and lower costs. This research will achieve both of these benefits because the results of the research will guide selection of a cost effective sampling design and use of statistical estimators that take advantage of combining airborne and satellite remote sensing to reduce variability of key sample-based estimates required of the CMS. The proposed work not only contributes to a more efficient and effective CMS but also contributes to the wider NASA mission of validating land cover and land change products.
Rationale: Mexico is a mega-diverse country where nearly 40% of its territory is covered by forests. The long-term impacts of land use and anthropogenic changes have fragmented and fundamentally transformed Mexican landscapes. Therefore, forests in Mexico are determined by climate gradients and land history creating a heterogeneous landscape. The most important land use change types having caused severe ecological degradation include: deforestation, high impact livestock grazing, and soil tillage. Furthermore, Mexico has shown an average rate of deforestation of nearly 550,000 ha year for the period 1993–2007 with a slight increase in natural forest regeneration, particularly in southern Mexico. It is estimated that gross primary productivity (GPP) of the conterminous USA is ~7 PgC, but Mexico's ecosystems uptake ~2.6 PgC yr-1 with only 1/3 of the USA land mass. During the last decade the scientific capacity of Mexican scientists has rapidly increased and state-of-the-art measurements on carbon dynamics are now available at representative landscapes, and nationally supported by remote sensing and a national forest inventory. Thus, the time is ripe to test different approaches towards a framework for monitoring, reporting and verification (MRV) to support implementation of REDD+ across a gradient of forests in Mexico.

Overall goal: to analyze carbon stocks and dynamics from ecosystem- to the regional-scale as well as characterize and quantify the errors and uncertainties across scales for the MRV to support implementation of REDD+ in Mexican forests.

Specific objectives: 1) standardize ongoing methodologies for upscaling forest inventories and carbon dynamics measurements across 6 intensive forest monitoring sites; 2) characterize and quantify the errors and uncertainties in measurements and ecosystem models (BESS, DNDC) and remote sensing approaches (MODIS) for upscaling purposes of carbon dynamics in Mexican Forests; 3) identify hot-spots suitable for REDD+ and assess the potential vulnerability and variability of carbon dynamics at the national scale for the last 13 years.

Approach: this proposal builds upon ongoing efforts by the USDA Forest Service (support by USAID and the Commission for Environmental Cooperation) and the University of Delaware to study carbon dynamics in ecosystems across Mexico. This proposal will consolidate collaboration with Mexican scientists across six intensive forest monitoring sites (Tier 3) representing different forest types (evergreen, deciduous, mix, mangrove). Detailed data, including forest inventory, LIDAR, and net ecosystem exchange (NEE; using the eddy covariance technique) is already available at most sites. First, this proposal will standardize/harmonize the available data across sites (forest inventory, eddy covariance). Second, we will validate biomass, NEE, and gross primary productivity (GPP) at the site level based on forest inventories and eddy covariance measurements with ecosystem models (BESS, DNDC), and remote sensing approaches (MODIS). Third, errors and uncertainties will be quantified at the ecosystem-level and at the regional scale for estimation of carbon socks and carbon dynamics across Mexican
forests. Finally, we will use 13 years of archived remote sensing information (MODIS 2000-2013) to identify hot-spots, extreme values and trends at the regional scale that will provide insights for establishment for REDD+ initiatives.

Significance: This proposal supports NASA carbon cycle research through validation of MODIS products through measurements of forest inventories, and cross-validation with other models. This study will generate harmonized datasets on carbon cycle science in Mexico to make them comparable to datasets available in the United States.

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**Tristram West/Joint Global Change Research Institute**

**Carbon Monitoring of Agricultural Lands: Developing a Globally Consistent Estimate of Carbon Stocks and Fluxes**

A comprehensive carbon monitoring system will likely include the integration of bottom-up and top-down estimates. Current bottom-up estimates for global agricultural lands often consist of individual inventory-based estimates per country. This results in a global bottom-up estimate that is not consistent in underlying soils or land cover data, methods of estimating carbon stocks and fluxes, or estimates of uncertainty. The proposed research will use off-the-shelf data, models, and remote sensing products to develop a global bottom-up, inventory-based estimate of carbon stocks and fluxes for agricultural lands, including vegetation and soils. The annual estimates will be generated using globally consistent datasets, C estimation methods, and methods for estimating uncertainty. Land area will be defined by a fusion of MODIS land cover data and inventory-based land area data. Methods will coincide with current national and international methods and protocols for compatibility with ongoing efforts in carbon monitoring, reporting, and verification. While these estimates can be used independently for synthesis and assessment reports, they can also be (a) used in conjunction with similar global data on forest carbon stocks and fluxes, thereby generating one comprehensive bottom-up, inventory-based estimates, and (b) used to evaluate the latest state-of-the-art monitoring components generated by NASA in the coming years. A scoping study will also be conducted to determine how the bottom-up, inventory-based estimate can be improved upon or integrated with other satellite-based bottom-up estimates, and how the global agricultural estimate can be integrated with previously conducted estimates on global forest carbon.