NASA Science Mission Directorate
Research Opportunities in Space and Earth Sciences – 2015
NNH15ZDA001N
A**.7 Carbon Monitoring System**

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 per year 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.

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

- Studies using remote sensing data products 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 and to assist in having existing products used for stake-holder activities. Priority will be given to proposals where potential stakeholders have in-kind contributions to ensure transfer of CMS activities into their own ongoing or future activity.

A total of 68 proposals were received, and 15 have been selected for funding. The total funding to be provided for these investigations is approximately $16.8 million over 3 years. For Fiscal Year 2016 funds, $4.9 million is allocated to these selected investigations and $5.1 million has already been allocated to existing commitments from prior CMS solicitations.

The investigations selected are listed below. The Principal Investigator, institution, and investigation title are provided.

Alessandro Baccini/Woods Hole Research Center Inc.
Time-Series Measurements of Biomass Change from InSAR (TanDEM-X), MODIS, and LiDAR Observations
15-CMS15-0052

Deforestation and forest degradation of tropical vegetation account for 6 -17% of global annual CO2 emissions to the atmosphere (Van der Werf et al. 2009). International policy mechanisms designed to address emissions from forest loss such as REDD+ require the ability to monitor not only emissions from deforestation but also from forest degradation as well as the uptake by vegetation. While much progress has been made in monitoring changes in forest area and carbon density, measurements of biomass loss due to deforestation and degradation, and increases due to uptake remain challenging. Here we propose to develop a novel methodology to monitor CO2 fluxes to the atmosphere from losses (due to deforestation and degradation) and gains (from vegetation uptake) for the Amazon Basin. The approach is based on a combination of the InSAR TanDEM-x Spaceborne Interferometer, MODIS, LiDAR and field measurements.

The overall objective of the proposed project is to address the research and development required for a multi-sensor, multi-spatial resolution monitoring system integrated with a carbon bookkeeping model to quantify CO2 fluxes to the atmosphere from land carbon dynamics. The specific objectives are to: 1) Quantify the correspondence between TanDEM-X phase height and biomass and derive biomass changes as a function of phase height variations. Using TanDEM-X data taken monthly and at 50-m resolution over Tapajos forest between 2011 and 2016, we will then determine the accuracy with which multi-temporal TanDEM-X observations can be used to measure biomass changes (losses and gains). To do this we will use existing field data and LiDAR measurements collected in the region; 2) assess the within-pixel sensitivity of MODIS derived biomass changes. We will build on Baccini et al. (2012; In Review) and derive annual biomass change estimates. We will then compare with high resolution change estimates from TanDEM-X and assess the sensitivity of MODIS to sub-pixel changes in biomass; 3) address the research and development required to combine InSAR spaceborne observations with MODIS reflectance. By combining time series of InSAR and MODIS observations we expect to increase the sensitivity in biomass change while expanding our monitoring capability over larger area; 4) assess the impact of differing resolutions and accuracies in biomass change estimates when products from objectives (1) and (3) are used in a bookkeeping model to derive CO2 fluxes.

Mark Cochrane/South Dakota State University
Continuation and Expansion to a National-Scale of the"Filling a Critical Gap in Indonesia's National Carbon Monitoring, Reporting, and Verification Capabilities for Supporting REDD+ Activities: Incorporating, Quantifying and Locating Fire Emissions from Within Tropical Peat-Swamp Forests" Project

15-CMS15-0054

Indonesia ranks as the 3rd largest CO2eq emitting nation, largely due to episodic uncontrolled fires within drained peat-swamp forests. The original project (NNX13AP46G) set out to 1) provide extensive field investigation of land cover, hydrologic, fuel and fire dynamics in a 120,000 ha REDD+ project in Central Kalimantan; 2) Collect a new LIDAR dataset to complement our existing 2007 and 2011 coverages; 3) Conduct groundbreaking detailed emissions field sampling of smoldering in-situ peat fires; and 4) Generate a fully parameterized and validated annual emissions model for the study region in support of its REDD+ project. Despite extensive bureaucratic and logistical challenges and delays inherent in working in Indonesia, objectives 1-3 have now been completed and the modeling efforts are ongoing with all necessary data now in hand as we complete the original project time period. However, our recent unprecedented emission findings (Stockwell et al. 2016), gained in situ during the height of the 2015 El Niño, have documented substantial differences between the actual regional peat fire emissions and existing emission factors, indicating regional Indonesian carbon equivalent emissions (100 year) may have been 19% less than current IPCC-based emission factor estimates. The IPCC emission factors are derived from one lab study burning peat from Sumatra (Christian et al. 2003) and considerable variation in emissions may exist between peat fires of Indonesia's three major peat formations highlighting the need for the additional field emissions measurements we intend to carry out in the continuation of the project proposed here.

We propose expanding to a national level, our successful regional (Kalimantan) CMS project (NNX13AP46G), to better advance Indonesia's Monitoring, Reporting and Verification (MRV) capabilities for peatland carbon emissions and support nationwide Reducing Emissions from Deforestation and Forest Degradation (REDD) efforts. We will implement our standardized field-based analyses of fuels, hydrology, peat burning characteristics and fire emissions, developed from our ongoing work in a 120,000 ha REDD+ project, to regionally parameterize our peatland emissions model for all of Indonesia's major peatland areas by including three new locations, Riau and Jambi (Sumatra) and Western Papua (Papua), for inclusion within the Indonesian National Carbon Accounting System (INCAS). We will conduct on-site whole air sampling of natural peat smoke plumes in situ for precise measurement of non-reactive greenhouse gases, collect peat samples just in front of these active peat fires, and burn the samples in the US while measuring aerosol mass and optical properties and reactive gases. This will create comprehensive and pertinent emissions factors (EFs) for each study region that will be critically important for assessing health impacts and total global warming potential (GWP) of these emissions. Remotely sensed land cover/change (Landsat) and surface fire ignition timing and locations (MODIS) provide spatial and temporal drivers for the modelled emissions that will now be validated/constrained at a national level using biomass burning emissions estimations derived from Visible/Infrared Imager and Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting Partnership (NPP) satellite and the new Japanese Geostationary Meteorological Satellite (Himawari-8). Multiple LIDAR datasets (2014, 2011, 2007) for Kalimantan are being used to quantify model accuracy, and new work will be undertaken to quantify uncertainty in our most

recent LIDAR-based digital terrain model (DTM), further improving assessments of modelling errors.

Bruce Cook/Goddard Space Flight Center
Remote Sensing as a Bridge to Operational Forest Carbon Monitoring in Interior Alaska
15-CMS15-0012

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—the largest 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 warming 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. The broader policy focus on land carbon sinks also encourages monitoring and accounting of the complete US land carbon sink, including Interior Alaska. Article 4 of the Paris Agreement recognizes the importance of "removals by sinks of greenhouse gases," and specifically requests that national inventories include information on removals.

Here, we propose to expand the joint NASA-USFS Pilot Project in the Tanana Inventory Unit, funded in part by ROSES-2013 CMS, to inventory a second USFS region in Interior Alaska, the Susitna-Copper River (SCR) Inventory Unit. Based on the success of the pilot project, the USFS has initiated a 10-year, $25M inventory plan for Interior Alaska using remote sensing data from Goddard's Lidar, Hyperspectral, and Thermal (G-LiHT) Airborne Imager (http://gliht.gsfc.nasa.gov). The proposed research leverages USFS funding for G-LiHT data collection. However, the USFS inventory activity does not support research collaboration between NASA and USFS scientists, data analysis, or methods development. The proposed CMS project supports the transition of lidar-assisted forest inventory activities from research to operations, targeting specific objectives for NASA's CMS program to use "remote sensing data products to produce and evaluate prototype MRV system approaches" and "studies that address research needs to advance remote sensing-based approaches to MRV" identified in Section 2.1 of the ROSES-2015 CMS solicitation (A.7).

The proposed project has five components. The first three activities represent a continuation of research themes and data products outlined in the NASA-USFS Pilot Project, including specific requests for core inventory products by the USFS Forest Inventory & Analysis (FIA) Program, a key stakeholder for this effort. Core project components include 1) collaboration between USFS and NASA scientists on experimental design for optimal integration of field and lidar data for forest carbon monitoring, 2) estimation of forest carbon stocks for the SCR Inventory Unit using established methods to combine plot and lidar data, and 3) development of new, spatially explicit estimates of carbon stocks and uncertainties using hierarchical Bayesian

statistical methods. In addition to these core inventory activities, we will use the combination of field inventory plots and G-LiHT data to 4) develop estimates of woody shrub biomass (e.g., alder and willow), a dominant feature of boreal forest landscapes that are not included in FIA inventory estimates, and 5) collaborate with USFS Forest Health experts to identify mortality and carbon losses from insects and disease (e.g., spruce bark beetle, aspen and birch leaf miners, birch leaf roller, alder dieback and canker disease). These additional project components target two specific needs identified by USFS scientists and stakeholders.

The main outcomes from this work will be estimates of total (live + dead) forest carbon stocks, including woody shrubs, and associated uncertainties for the SCR Inventory Unit of Interior Alaska. These estimates provide critical and timely information for carbon monitoring and resource management, and baseline conditions for the spatial distribution of vegetation carbon stocks in a region undergoing rapid climate change.

Riley Duren/Jet Propulsion Laboratory
Prototype Methane Monitoring System for California
15-CMS15-0062

We propose to leverage a planned project with California stakeholder agencies to develop a prototype methane monitoring system for the state. The California Air Resources Board (CARB) and the California Energy Commission (CEC) are funding JPL to conduct a baseline survey of methane super-emitters across the state in late 2016 using proven airborne imaging spectrometers. The California Baseline Methane Survey will produce a data set of geolocated methane plume images for super-emitter sources. We propose to build on and dramatically improve the relevance of that data set by developing and validating point source flux estimates, uncertainty estimates, linking that information with multi-scale attribution data and regional flux estimates derived from other CMS and NACP projects (that employ satellite and surface observations), and coordinating with California stakeholder agencies to infuse those products into their decision-making frameworks. We will also work with a broader set of stakeholders to evaluate the potential future application of this Prototype Methane Monitoring System in other key regions in the US and internationally.

Our proposed development of a Prototype Methane Monitoring System for California is of immediate societal relevance and significance given growing priorities to account for and mitigate methane emissions. The recently approved California law AB1496 states that "there is an urgent need to improve the monitoring and measurement of methane emissions from the major sources in California" and directs the California Air Resources Board to "undertake, in consultation with districts that monitor methane, monitoring and measurements of high-emission methane hot spots in the state using the best available and cost-effective scientific and technical methods". Hence this project is directly responsive to that policy by addressing methane hot spots (super-emitters), by establishing a close collaboration between local, state, and US national stakeholders and by applying the best available scientific methods (including remote sensing derived point

flux estimates and integration with other data sets across multiple spatial scales and emission sectors).

The planned use for this data set by stakeholders spans multiple governance levels, emission sectors and programs – ranging from EPA Region 9's interest in livestock emissions under the EPA AgStar program (the largest methane emission sector in California) to SC-AQMD's focus on landfills, oil and gas (both for methane and potential co-emitted criteria pollutants). Similarly, the proposed end-to-end, multi-scale approach will also help explore and path-find the potential future extensibility of these methods to other regions in the US and internationally – addressing key US national priorities (US-Canada Joint Statement, 2016; President's Climate Action Plan, 2013).

Christopher Elvidge/National Oceanic and Atmospheric Administration, Silver Spring
Global Monitoring, Reporting, and Verification (MRV) System for Carbon Emissions from Natural Gas Flaring
15-CMS15-0016

NOAA has developed a prototype MRV (monitoring, reporting and verification) system for global gas flaring. The purpose of this project is to reduce the uncertainties in the carbon emission estimates and produce a consistent time series of annual CO2 emission estimates for individual flare sites spanning 2012 through 2018. The monitoring system is based near-infrared and short-wave infrared nighttime data collected by the Visible Infrared Imaging Radiometer Suite (VIIRS). Peak radiant emissions from gas flares occur near 1.62 um - center of the VIIRS M11 spectral band. Using detections in multiple spectral bands, the algorithm calculates temperature, source size and radiant heat. Flares are separated from biomass burning and industrial sites based on temperature and persistence. More than 7000 flares were found each year in 2012-2014. Fire each flaring site, annual average radiant heat is calculated from the cloud-free observation set. The current calibration is based on national level flaring data reportd by Cedigaz. The uncertainty in the current estimates exceeds the year-to-year differences in flared gas volumes from individual countries, calling into question the estimates. It is believed that the large uncertainties arise from country level errors in the Cedigaz estimates.

Methods: Nighttime VIIRS data will be collected on a series of test flares burning a precisely controlled natural gas flow rates. Measurements will be made over a range of view angles and three flow rates (low, medium and high). Additional test flare events will explore the effects of multiple flares inside a VIIRS pixel and the effects of black carbon. From this test set, a new calibration will be developed for estimating flared gas volumes. The calibration will then be applied to VIIRS data spanning 2012-2018 resulting in both site specific and national estimates of CO2 emissions from natural gas flaring.

Significance: The project meets on of the primary calls in the announcement – for proposals to develop MRV systems using remotely sensed data. There are three primary applications for the gas flaring MRV:

A. Emission reductions to meet Intended Nationally Determined Contributions (INDC): Countries need to have historical records and annual updates of their CO2 emissions from gas flaring. The data will be used to gauge the level of effort to be placed on gas flaring reduction. For countries with large flaring emissions, reductions in flaring may be enough to meet their INDC. Other countries with small flaring volumes may decide to focus their efforts on achieving their INDC targets in other sectors. Accurate gas flaring emission data are key to these decisions. The MRV data will also be used to document the INDC emission reductions from gas flaring.
B. Zero Routine Flaring by 2013: The gas flaring MRV data are crucial this initiative. The MRV data will be used to identify the routine flares. This will likely be done based on duty cycle. Certainly flares detected 50-100% of the time are routine. As the duty cycle declines, at some point the flare will be deemed to be œnon-routine. The VIIRS data can be used to distinguish routine versus non-routine flaring once a decision has been made on the duty cycle threshold. For the routine flares, these can be tracked over time to document changes indicating the flare has been extinguished or converted to non-routine status.
C. Low Carbon Fuel Standards (LCFS): Site specific MRV data can be assigned to specific production fields as one of the data sources used to calculate the carbon intensity of fuels. This approach can be used to establish flaring baseline for specific production fields and tracking of changes in flaring that count towards carbon emission reductions.

Temilola Fatoyinbo/Goddard Space Flight Center
Future Mission Fusion for High Biomass Forest Carbon Accounting
15-CMS15-0055

Objectives
The primary objectives of our research are: (1) To independently quantify the relationship between biomass density and expected error from GEDI, NISAR and ICESat-2 in high AGB forests in Sonoma County, Costa Rica, and Gabon; (2) To identify the sources of error in high biomass forests for each mission, including from field estimates (GPS error, allometry), from errors in the airborne/spaceborne data (penetration to the ground), and from errors in empirical modeling; (3) To assess data fusion techniques in order to increase the accuracy of AGB estimation through the integration of the airborne simulators for the three missions; (4) To provide AGB stock and error maps to local stakeholders through a user-friendly web portal, enabling the estimation of total AGB and expected error specifically within areas of local interest.

Methods/Techniques
The proposed research focuses on establishing the relationship between AGB density and estimation error for each of three future active remote sensing NASA missions using three study areas with high AGB forests. We propose to use existing airborne datasets that have been collected over forests in Gabon, Costa Rica, and Sonoma County, and to process these datasets to simulate NISAR, ICESAT-2, and GEDI.

Field data have already been collected in all three study sites. New field data will also be collected in particularly high biomass areas of Sonoma County. Finally, Terrestrial Laser Scanning (TLS) data will be collected in Sonoma County, as well as provided to the research team from existing collections in Gabon. This TLS data will quantify existing or expected errors in field estimates of AGB.
LVIS and discrete return Airborne Laser Scanning (ALS) data are the data sources used to simulate GEDI, through a GEDI waveform simulator already under development at the University of Maryland. LVIS data has already been collected in Costa Rica and Gabon, and ALS has been collected in Sonoma County. ALS data will also be used to simulate ICESAT-2's ATLAS dataset, through a photon counting simulation already tested using ALS data in Gabon. This simulation will be expanded to Sonoma County. Finally, UAVSAR will be used to simulate NISAR. Metrics gleaned from each simulation product will be used to build mission-independent AGB stock and error models for each of the three datasets.
Finally, a prototype design for future mission fusion will be developed to capitalize on the three independent sets of structural observations from GEDI, ICESAT-2 and NISAR. All AGB and error maps will be provided to local stakeholders via a cloud-based GIS software package, Ecometrica, which will enable the manipulation of maps to perform carbon accounting for locally relevant land management activities.

Perceived Significance
Through comparing future mission utility on a shared set of field observations, the proposed research will provide a precise and comparable quantification of expected errors from GEDI, ICESAT-2, and NISAR in high AGB forests. Additionally, methods will be tested to fuse these three future datasets with the intention of developing best practices for AGB and error MRV. By working with scientists from each of the three missions'science teams, this research will provide an unbiased analysis of the strengths and weaknesses of the future missions and inform the development of the next generation of NASA active RS instruments. Additionally, by working with local stakeholders both in the US and abroad, the proposed research will facilitate knowledge and data transfer from data developers to data users in the hopes that best practices can be developed to optimize the utility of future missions products for carbon monitoring initiatives, such as REDD+.

Roberto Izaurralde/University of Maryland, College Park
Cropland Carbon Monitoring System (CCMS): A Satellite-Based System to Estimate Carbon Fluxes on U.S. Croplands
15-CMS15-0063

Croplands are considered to have large CO2 offset capacity. However, it is highly uncertain how much CO2 stabilization can be achieved through land management strategies as croplands are expected to meet increasing demands for food and bioenergy production. The impacts of land use and land management practices on carbon (C) cycling should be anticipated when developing recommended strategies and policies; otherwise, they may induce unintended loss of CO2 to the atmosphere and render croplands as C sources. Lack of a cropland C monitoring system that captures the complexity of cropland C cycling and provides fine-scale and accurate C flux estimates

hinders the development of effective joint policies and integrated sustainable carbon management strategies targeting CO2 offset potentials.
Current methods for cropland C monitoring yield unreasonable regional flux estimates as they lack spatially resolved crop parameters and management practices. Satellite remote sensing is a strong tool for estimating spatially distributed vegetative characteristics (e.g. crop phenology and LAI) and crop parameters (e.g. land cover and land use change, crop species, crop rotations) used in agroecosystem models. As part of the Global Agricultural Monitoring (GEO-GLAM) program, which is jointly funded by NASA and USDA, we have developed a remote-sensing version of the mechanistic agroecosystem model EPIC, herein referred to as RS-EPIC, which utilizes satellite remote sensing data to improve crop characterization and simulation of crop productivity, soil C storage and C fluxes.
The overall scientific goal of this proposal is to develop a Cropland C Monitoring System (CCMS) prototype that improves upon cropland C storage and flux estimates developed under previous NASA CMS activities in terms of spatial and temporal scale and completeness. As a first objective of this goal, we will integrate satellite-derived crop specific characterization of vegetation and management, off-shelf ancillary spatial databases and the RS-EPIC model to estimate seasonal and annual C cycle components including net primary production (NPP), net ecosystem productivity (NEP), harvested C, lateral soil C fluxes and net ecosystem C balance (NECB). These estimates will be produced for corn, soybean, wheat, sorghum, cotton, alfalfa, barley, rice and peas crops grown in the conterminous US at a spatial resolution of 500 m for 2015-2016. Together, the nine major crops grown cover approximately 96% of US cropland area. Three additional objectives are: 1) estimate uncertainty of C storage and fluxes estimated by the CCMS prototype; 2) engage with national agencies to evaluate the CCMS consistency with existing C inventories; 3) conduct a scoping study to evaluate remote sensing methods for mapping soil tillage at large scales.
Ultimately, the CCMS products developed under this project will provide the knowledge base at relevant spatial and temporal scales for understanding complex C cycling outcomes under various land use and land management practices and developing joint policies to meet multiple objectives (e.g. food and energy security) while contributing to stabilize atmospheric CO2. Other potential uses of the CCMS include: 1) use in economic models to determine incentive levels for C management options; 2) integration into hydrological models to assess impacts on aquatic ecosystems; 3) incorporation into regional integrated assessment models to understand contributions of regional management practices to global climate change; 4) use of NPP estimates to interpret the top-bottom CO2 estimates 5) enhancement of EPA reporting of CO2 offset potentials on croplands.

Stephan Kawa/Goddard Space Flight Center
Airborne Eddy Flux Measurements for Validation/Evaluation of High-Resolution MRV Systems
15-CMS15-0019

Progress in the Carbon Monitoring System (CMS) demands rigorous evaluation and quantitative uncertainty characterization in all products and analyses. A range of validation approaches is used, but comprehensive evaluation is challenging, often limited

in coverage, representativeness, and precision. The guiding science question for this proposal is: how best to validate CMS regional-scale products and how well can this be done?

We aim to expand the current scope of validation methods for CMS through acquisition and analysis of airborne eddy covariance carbon flux observations. Specifically, we will address the question: How can real-time flux measurements over regional length scales contribute to validation of the products and processes inherent in designing a high-resolution Monitoring, Reporting, and Verification (MRV) system? We will do this within the framework of a prototype system for monitoring carbon stocks and fluxes under development for CMS at the University of Maryland (UMD).

Airborne eddy covariance is a powerful observational tool capable of providing near-direct measurements of surface-atmosphere exchange at ecosystem and policy relevant scales of 1 – 100 km. Our group at GSFC has assembled a system for measurement of CO2, CH4, H2O, and heat fluxes based on the NASA Sherpa aircraft. The Sherpa provides a versatile, economical platform for measuring greenhouse gas (GHG) fluxes to be used in evaluating top-down and bottom-up source/sink estimates for a wide range of applications, including evaluation of biophysical process models as well as validation of top-level satellite flux products from OCO-2 and other carbon space missions. The system is supported and scheduled for installation, flight-testing, and science demonstration over the Maryland Eastern Shore during July-Sept 2016.

To address uncertainties in the high-resolution MRV system we will focus on measuring and evaluating the ecosystem model processes used to connect vegetation metabolism to biomass change and, hence, integrated carbon flux. The analysis will compare flux data and modeling across gradients of forest height and type as well as soil and climate regime within the US Mid-Atlantic region. We will also use the airborne flux data to assess uncertainties in scaling up from local to regional and larger domains. This will include leveraging of the flux data acquired in 2016 under separate funding as well as acquisition of additional airborne flux data. The latter will be guided by sensitivities identified in the carbon stock and modeling surveys of the UMD prototype system. We will also assess the measurement requirements for airborne flux observations to quantify net carbon emissions and storage.

The impact of this project will be to advance the primary CMS goal of evaluation of errors and uncertainties by demonstrating a potentially powerful tool for flux quantification applicable to CMS. We will produce a data set of regional GHG flux estimates and their statistical errors for use in other CMS and community analyses, and we will provide a more comprehensive validation/evaluation of uncertainties in the UMD prototype MRV products. The measurement technique is also potentially applicable to validation for CMS Integrated Emission/Uptake (‘Flux’) products. This research directly addresses the CMS solicitation request to advance remote sensing-based approaches to MRV through use of airborne flux observations as an alternative method for quantifying net carbon emissions, and the need to improve the characterization and quantification of errors and uncertainties in existing NASA CMS products. The work is timely both for maturation of the MRV prototype system to include a better description of uncertainties as well as to make use of a new experimental capability for the corresponding domain.

Robert Kennedy/Oregon State University
Tools to Bridge the Gap Between Static CMS Maps, Models, and Stakeholders
15-CMS15-0027

From its inception, the NASA Carbon Monitoring System (CMS) has largely been organized around two activities: observation-based mapping of biomass and model-based estimation of carbon flux. Although there has been significant progress in both biomass and flux activities at various scales, several challenges hinder the use of biomass products to inform flux modeling. Challenges include: biomass maps are often static or local scale, uncertainties are difficult to render and incorporate into models, and map products are not designed with the needs – and format standards – of modelers in mind.

To help address these challenges, we propose a set of research activities organized around two objectives. First, we will develop tools to integrate static and dynamic CMS products of any temporal, spatial, and semantic content into a consistent, continental-U.S.-wide, derived database of yearly land cover, biomass, disturbance and growth in terrestrial systems, along with spatially explicit and consistent uncertainties. These can be used to set states, hone parameters, schedule events, and constrain or benchmark models from which flux estimates ultimately are derived. Second, we will develop a smart application programming interface to allow modelers and stakeholders easy access to these data in the spatial, temporal, and information domain they require.

We have assembled a team of Collaborators and Co-Investigators to help guide success. Collaborators include numerous CMS colleagues who have produced or are producing the static or local-scale maps we will integrate into our yearly maps. They will ensure we interpret and use their products appropriately. Co-Investigators include process-level modelers who represent a series of carbon use-cases, ranging from regional scale DGVM implementations to global scale, multi-model ensembles. They will help develop and test the interface to ensure its applicability across a continuum of situations, and will help guide us toward visualization choices appropriate for their stakeholders. Finally, we have engaged key representatives from the Land Processes and Oak Ridge National Lab Distributed Active Archive Centers (LP and ORNL DAACs) to ensure that our interface complements and co-exists with the data access and archiving efforts they continue to lead.

Key deliverables include:

- A database of 30m resolution, yearly time-step maps from 1990 to present of forest biomass, land cover, tree cover, crop type, and disturbance for the continental U.S., along with uncertainties
- Computational interface (API) to allow CMS participants to easily access and analyze that database
- Assessment of potential improvement in models derived from these dynamic land surface drivers, including possible reduction in uncertainties.

This efforts explicitly addresses the CMS call for follow-on to existing CMS efforts, for development of new remotely-sensed MRV-relevant products, and for improvement of carbon modeling capacity.

John Lin/University of Utah, Salt Lake City
Towards a Complex Terrain Carbon Monitoring System (CMS-Mountains): Development and Testing in the Western U.S.
15-CMS15-0028

Despite the need to understand terrestrial biospheric carbon fluxes to account for carbon cycle feedbacks and predict future CO2 concentrations, knowledge of these fluxes at the regional scale remains poor. This is particularly true in mountainous areas, where complex atmospheric flows and relative lack of observations lead to significant uncertainties in carbon fluxes. Yet many mountainous regions also have significant forest cover and biomass—i.e., they are areas with the potential to serve as terrestrial carbon sinks. However, these sinks are highly dynamic and vulnerable to disturbance events, such as drought, insect damage, and wildfires. A strong need exists for the use of satellite remote sensing and modeling to help shed light on carbon dynamics in regions of complex terrain.

Recent remote sensing advances from NASA can now be used to address the observational gap in mountainous areas. First, column-averaged CO2 (XCO2) yields atmospheric constraints on modeled biospheric fluxes in regions where in-situ CO2 observations are absent. Second, retrieval of Solar-Induced Fluorescence (SIF) from space has provided a powerful means to sense physiological signals of gross primary productivity (GPP) at regional to global scales. However, the relationship between SIF and GPP is complicated, and current uncertainties prevent scaling of well-established leaf-level fluorescence mechanisms to interpret GPP at larger scales, especially for coniferous species.

Our proposed research will address the following key scientific questions:

1) How can satellite, atmospheric in-situ, and ecological observations be combined with atmospheric and biospheric models to inform carbon budgets in regions of complex terrain?
2) How is satellite-retrieved SIF related to leaf-level physiology?
3) What are the impacts of drought on carbon cycling in mountainous regions?

We propose development and testing of a new Carbon Monitoring System over Mountains (CMS-Mountains) covering the Western U.S., where we will leverage numerous existing efforts in biospheric and atmospheric modeling. We will run the Community Land Model (CLM) at high spatial resolution, assimilating satellite observations of SIF, leaf area index, and snow cover within the Data Assimilation Research Testbed (DART). Signals of simulated biospheric fluxes from CLM-DART will be compared via atmospheric modeling to remotely sensed XCO2. Discrepancies will be minimized through adjustment of the regional fluxes as part of an atmospheric inversion.

In this way, CMS-Mountains will deliver estimates of regional scale carbon fluxes over the Western U.S., along with their uncertainties, constrained by remotely sensed datasets.

While the proposed project will focus on the Western U.S., the framework we develop will be applicable elsewhere. We anticipate the CMS-Mountains platform will ultimately be applied to other regions of complex terrain around the world, driven by remote sensing data in the absence of in-situ measurements.

This project directly addresses the objectives of NASA's CMS program, as mentioned in the proposal call. We are proposing a study that uses "remote sensing data products to produce and evaluate prototype MRV system approaches". It will contribute towards "U.S. national efforts toward integrated carbon monitoring" by helping to constrain the U.S. carbon budget for a region that is poorly understood (Western U.S.). Moreover, our project will help "improve the characterization and quantification of errors and uncertainties in existing and/or proposed NASA CMS products" for regions of complex terrain. To our knowledge, existing CMS projects either have a global scope or focus on regions outside of mountainous areas. By focusing on the carbon budget in the Western U.S., an area of complex terrain, our project will help quantify the magnitude and sources of uncertainties in other CMS products over this area.

Jeffrey Masek/Goddard Space Flight Center
CMS Applications: Stakeholder Engagement and Analysis of CMS Data Products in Decision Making and Policy Frameworks
15-CMS15-0021

Our team seeks to build upon and expand the current Carbon Monitoring System (CMS) Applications project (Escobar-2013) that assesses, identifies, and appropriately links existing decision support processes and policies to CMS carbon science. This CMS Applications effort aims to serve as a vehicle for facilitating and translating critical NASA science into decision support systems, establishing the science maturity and application readiness for NASA Headquarters and clearly stating the impact of CMS science to society for Congress. The partnerships fostered though this effort will lead to better utilization of NASA CMS data products, in turn leading to positive financial and societal outcomes.

Our proposed work is highly relevant to the following activities listed as priorities for this call:

1) understanding and engaging the user community for carbon monitoring products;
2) evaluating current and planned NASA CMS products with regard to their value for decision making by identified users and to assist in having existing products used for stakeholder activities;
3) conducting MRV-related work in support of international REDD or REDD+ projects, as well as studies of stakeholder interests;
4) assessing the NASA CMS applications program though a "lessons learned" document which evaluates the number of potential and actual CMS data users.

During the next phase of funding our team will focus efforts on several fronts. First, we will continue to develop the translation tools created during the Escobar-2013 project, and relate CMS product capabilities to stakeholder needs through the use tutorials, short science articles, white papers, and policy briefs. that identify thematic opportunities, identify data gaps and sync the CMS science research to the beneficiary of the data (stakeholder). Workshops events and the CMS Policy Speaker Series will continue to serve as tools for highlighting carbon relevant policies and identifying the science needs of operational organizations. Furthermore, we will develop a systematic evaluation of these workshops and policy series with follow-up surveys and reports in an effort to assess the societal relevance of our activities

Our team will conduct science policy bridging with organizations such as (but not limited to) RGGI, EPA, USGS, 3DEP, USGCRP, Chesapeake Bay Restoration Program, USDA Environmental Markets and the Department of Natural Resources for Maryland, Delaware, Pennsylvania and Sonoma County, CA and USGCRP. These partners were identified in the Escobar 2013 Applications work and a clear understanding of their needs and objectives will be expanded on for the 2016 efforts. We will also collaborate closely with the Carbon Cycle Interagency Working Group of the U.S Global Change Research Program, and contribute to carbon-related reports, such as the SOCCR-2 and the Fourth National Climate Assessment.

Of equal importance is merging the diversity of the CMS Initiative with ongoing and future NASA missions and programs. These cross-mission collaborations are essential for broadening the reach and relevance of CMS science. The proposed CMS Applications effort will leverage opportunities with newer missions like SMAP and OCO-2 while also planning for future synergy with ICESat-2, NISAR and ASCENDS.

Finally, research to assess the impact and value of the CMS data in specific case studies will be conducted in collaboration with the Joint Global Change Research Institute (JGCRI), collaboration between the U.S DoE Pacific Northwest National Laboratory (PNNL) and the University of Maryland at College Park.

John Miller/Office of Oceanic and Atmospheric Research, Boulder
Disaggregating Amazon Basin Fire Fluxes Using Remote Sensing of Atmospheric Carbon Monoxide and Burned Area
15-CMS15-0053

We propose to use the combination of remote sensing of atmospheric carbon monoxide (CO) from three different satellite sensors -- MOPITT, IASI and TROPOMI -- along with state of the art, high resolution, maps of burned area to determine fire emissions over the Amazon Basin, spatially, temporally, and by fire type. These data will be used with a data assimilation system that will appropriately scale burned area maps to match both in situ and satellite CO data. Calculating emissions from different fire types will allow us to better understand the net climate impact of fire emissions in the Amazon Basin (note that

not all fire emission have a net climate impact). Note that while fire emission modeling approaches based on burned area, like CASA/GFED also calculate fire by type and region, they are based on coarser land surface maps. They also likely underestimate understory fires have trouble identifying fires during high aerosol loading and persistent cloud cover. In contrast, an atmospheric approach, based on measurements of CO and high resolution burned area maps, will allow for integration of carbon emissions from various types of fires, whether or not they can be easily detected from space.

Fire carbon emission by type and area will be a valuable addition to existing methods used to calculate forest carbon emissions as part of REDD (Reducing Emissions from Deforestation and forest Degradation) projects. To this end, we will also conduct a stakeholders workshop involving Brazilian scientists and climate policy representatives to communicate our results and approach and learn about their information needs. The policy-relevant scientific research and stakeholder outreach we propose are both closely aligned with the goals of NASA's Carbon Monitoring System (CMS).

Specific project deliverables proposed include development of novel burned area products at high resolution from 2010-2018 that will allow for improved classification of burned area and inclusion of hard to detect fires, such as understory fires, in burned area maps. On the atmospheric side, we will conduct a thorough bias assessment of the satellite data using in situ CO data, allowing us to apply bias correction algorithms. Bias corrections are critical to ensure that gradients in the spatially dense CO data are geophysical and do not result in flux biases. Moreover, bias corrected satellite CO products will be made available to the broader community.

Thomas Nehrkorn/Atmospheric & Environmental Research, Inc.
Prototype Regional Carbon Monitoring Systems for Urban Regions
15-CMS15-0022

The 2015 COP21 meeting in Paris fundamentally changed the approach to carbon monitoring, reporting, verification and validation (MRV/MRVV). The emphasis on voluntary measures, and the large number of ongoing GHG reduction efforts at sub-national levels in government, non-profit, and private sectors, require monitoring capability at policy-relevant scales: region, state, and city. Urban regions are particularly important because cities account for more than 70% of all global fossil-fuel CO2 emissions, and urban losses of natural gas CH4 equal or exceed emissions from production and processing.

We propose research to develop a prototype MRV system for Boston and the urban Northeastern US, leveraging results of our current CMS project. We will advance our framework and help deploy a similar system in the San Francisco Bay Area, collaborating with the Bay Area Air Quality Management District (BAAQMD). Both cities have strong GHG reduction efforts (Boston's plan was honored at COP21, and the BAAQMD has ambitious GHG reduction goals for their 10-point Climate Action Work Program). We propose new or enhanced capabilities in four key areas: (1) observational networks that

combine ground-based remote sensing from new solar-viewing spectrometers and Lidar with observations from space-borne platforms (OCO-2, OCO-3, TROPOMI, and CALIPSO) and in situ networks; (2) novel bottom-up approaches to generate high-resolution flux inventories in urban and surrounding areas; (3) a high-resolution transport modeling (WRF-STILT) framework, coupled to inversion algorithms to provide posterior estimates of fluxes and uncertainties on scales from urban region to neighborhood; and (4) strong engagement with stakeholder communities and local and state entities.

Quantification and reduction of uncertainties are a key focus. We assess bottom-up inventories by comparing with independent estimates; verify meteorological fields used for transport modeling against a wide range of observations; and undertake intensive field studies to quantify systematic errors in emissions estimates.

The San Francisco Bay area and Boston have contrasting meteorological (e.g., marine vs. continental inflow) and biophysical characteristics (e.g., biomes, seasonality, topographical heterogeneity). We plan an intensive study in the Bay Area under auspices of the BAAQMD, and will focus on transferring to the District methods we have developed for bottom-up inventories at high resolution and elements of our network design and analysis. This work will help us to apply our techniques and findings from the Northeast to elsewhere in the US and the world.

We will assess the MRV capability of column-integrated measurements, both from new ground-based FTS instruments, and space-borne platforms (OCO-2 and OCO-3). Our transport modeling framework will take advantage of recent advances in the treatment of near-field emissions and high-resolution modeling for urban areas. Our proposed bottom-up inventory approach for anthropogenic emissions leverages working relationships with stakeholders to enable use of non-standard activity data, and it treats previously neglected sectors (urban biosphere, human respiration) needed to interpret observational data. We plan to widen stakeholder interactions and address user needs by involving interested parties through exposure to pilot data products and methods transfer.

Our proposal addresses core goals of the NNH15ZDA001N-CMS solicitation: "using remote sensing data products to produce and evaluate prototype MRV system approaches" and "studies to improve the characterization and quantification of errors and uncertainties [...] in the algorithms, models, and associated methodologies", and "studies of stakeholder interests and requirements". The proposed work will benefit from the team's involvement with the OCO-2 Science Team, the Environmental Defense Fund Methane Initiative, and the CMS project led by Dr. A. Andrews.

Pontus Olofsson/Boston University
Tracking Carbon Emissions and Removals by Time Series Analysis of the Land Surface: Prototype Application in Tropical MRV Systems Compliant with IPCC Tier 3
15-CMS15-0032

Many tropical countries are experiencing high rates of forest disturbance with of cycles of degradation, cultivation and recovery, but neither the activities nor the terrestrial carbon dynamics associated with the activities are properly tracked in existing REDD+ related Measurement, Reporting and Verification (MRV) systems. This situation is especially true for post-disturbance landscapes and degraded forests, as the trajectories of the land surface activities and carbon dynamics following disturbance are gradual in nature and inherently difficult to monitor. We propose to improve modeling of the carbon dynamics of areas that have experienced disturbance by combining a time series-based approach for monitoring changes on the land surface with a spatially and temporally explicit carbon bookkeeping approach. We have developed algorithms that track the land surface by analyzing time series of all available observations from the Landsat sensors complemented by data from space-borne radar instruments and other optical sensors. Implementations are currently underway across the United States and the Colombian Amazon. Additionally, we have developed open source software tools and educational materials that provide detailed hands-on instructions in support of capacity building efforts in collaboration with SilvaCarbon.

We propose a novel framework for estimation of carbon emissions and removals by including detailed information on the fate of the landscape. We will modify a recently developed bookkeeping model so that it runs at the pixel-level (spatially explicit) by directly integrating the results of time series information on conversion between land categories and forest degradation. The characterization of post-disturbance tropical landscapes is critical for accurate accounting of terrestrial carbon pools and fluxes because of the high productivity and carbon density of forests in this region. Therefore, in addition to the time series analysis of the land surface, the temporal dynamics of vegetation structure and recovery following disturbance will be investigated using existing space-borne lidar data in combination with data from upcoming NASA lidar missions. Following best practices protocols for statistical inference of change in area and carbon emissions, unbiased estimates with the uncertainty quantified in the form of confidence intervals will be constructed. Prototype applications of the proposed methodology will be implemented in Colombia and Cambodia, two tropical countries representing different levels of capacity and different types of forest disturbance. A SilvaCarbon effort is underway to complete a comprehensive time series-based analysis of the conversions between the land categories and post-disturbance landscapes across the Colombian Amazon that will be used together with a set of existing field measurements of biomass in a prototype application of the proposed methodology. The methodology will be implemented in Cambodia, where field-measured data on biomass are scarcer, capacity needs greater and the rate of deforestation and forest degradation higher. Engagement with stakeholders and countries will be enhanced by collaboration with in-country SilvaCarbon activities focused on enhancing and supporting systems of MRV for REDD+ activities (including the provision of input for designing field measurement programs). In addition, a spatially and temporally explicit model for estimating the carbon dynamics related to land surface activities will be added to the open source suite of software to provide a more complete framework for the enhancement of MRV systems in the tropics.

Sassan Saatchi/Jet Propulsion Laboratory
Annual GHG Inventory and MRV System for the US Forestlands
15-CMS15-0065

We propose to use the CMS infrastructure developed in our earlier pilot project and MRV prototypes to perform an updated annual Green House Gas (GHG) inventory of the US forestlands and contribute to the existing national MRV and the US Forest Service and the Environmental Protection Agency (EPA) national reporting to the United Nation Framework Convention on Climate Change (UNFCCC). The proposed work will produce spatial products on carbon stocks and fluxes that include stakeholder requirements on attributions and uncertainty and deliver at low-latency in order to be integrated in the national carbon management, decision making, and the official national MRV system. With the participation of stakeholders in the process of developing the products, for the first time, NASA CMS program will have the opportunity to directly contribute in the national GHG inventory.
The overall objectives of the proposed work are:

1. Develop spatial products on carbon pools and fluxes over the US forestlands including Alaska with the low latency to be used for annual reporting
2. Quantify all sources and sinks and attributions by combining spatial data on forest cover change, pools, and fluxes into the CARDAMOM model data fusion framework
3. Quantify and report uncertainty for all components of sources and sinks in the US forestlands
4. Benchmark the methodology and products for integration in the national MRV system and future stakeholder's activities.

The proposed CMS activity will advance the remote sensing techniques and product by: 1) quantifying changes of forest cover with all natural and anthropogenic attributions at the annual cycle with low-latency delivery, 2) integrating remote sensing and in-situ observations on carbon pools and fluxes in a diagnostic ecosystem carbon balance model to improve carbon sinks and sources for different attributions associated with annual changes in the US forestlands, 3) improve characterization and quantification of errors and uncertainty following the IPCC good practice guidelines, and 4) including stakeholders interests and requirements by directly involving the user community and allowing the evaluation of CMS products for decision making and integration in the national MRV system.

By including Alaska, the proposed work will use satellite and airborne and existing in-situ observations to compensate for the lack of extensive forest inventory data and provide, for the first time, the GHG inventory including all pools and fluxes, for both managed and unmanaged forests of the region. The methodology, including the CMS infrastructure for data processing, analysis, uncertainty assessment and data products will be benchmarked to allow integration in national MRV system. The benchmarking will

also provide transparency in the entire performance of the carbon monitoring infrastructure for reporting and verification in future carbon trading protocols.