NATIONAL STRATEGY TO ADVANCE AN INTEGRATED U.S. GREENHOUSE GAS MEASUREMENT, MONITORING, AND INFORMATION SYSTEM

A REPORT BY THE GREENHOUSE GAS MONITORING AND MEASUREMENT INTERAGENCY WORKING GROUP

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Executive Summary

The United States has committed to ambitious greenhouse gas (GHG) emissions reduction targets as part of the Nation's agenda to tackle the climate crisis. Enhancing GHG measurement and monitoring capabilities is foundational to achieving these ambitious goals. Doing so will improve the Nation's ability to track progress towards GHG emissions targets and assess the effectiveness of climate policies and actions. Numerous GHG measurement, monitoring, and data capabilities currently exist but are spread across various federal and non-federal entities. The Nation has the opportunity to enhance coordination and integration of these capabilities, make more efficient use of resources, and leverage recent scientific and technological advances to provide more comprehensive, granular, and timely data to support climate action.

The *National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System* seeks to guide collective efforts by providing the following:

- A conceptual framework for a U.S. GHG Measurement, Monitoring, and Information System (hereafter referred to as U.S. GHGMMIS or GHGMMIS).
- A set of national objectives to focus collective GHG measurement and monitoring efforts for federal and non-federal entities.
- A phased implementation approach that maximizes the use of mature capabilities today, while paving the way for future GHGMMIS advancements.

An integrated U.S. GHGMMIS consists of capabilities and activities from three core components: 1) GHG data derived from activity-level estimates and/or atmospheric measurements, 2) standards and methods for quality assurance and quality control, and 3) modeling of systems and activities that produce GHG emissions and removals.[a] This National Strategy seeks to leverage existing work and accelerate integration of the three core components in order to provide high-quality GHG information to government and nongovernment users on a sustained basis. The U.S. GHGMMIS will rely on the coordinated use of both atmospheric- and activity-based approaches as well as engagement with stakeholders to better understand evolving needs for GHG information and how the GHGMMIS can be responsive to those needs.

The National Objectives for Advancing the GHGMMIS will help focus and integrate efforts by federal government agencies and non-federal actors including city, state, and Tribal governments; academia; NGOs; philanthropies; and the private sector to implement a U.S. GHGMMIS. The National Objectives include the following:

[a] Throughout this report, references to greenhouse "emissions" should be interpreted as "net emissions," i.e., also including greenhouse gas removals.

- Objective 1: Improve activity-based (“bottom up”) GHG quantification approaches[b]
- Objective 2: Improve atmospheric-based (“top down”) GHG quantification approaches[c]
- Objective 3: Coordinate the use of activity- and atmospheric-based approaches to move towards convergence of GHG estimates
- Objective 4: Improve latency, completeness, interoperability, and accessibility of GHG data
- Objective 5: Support development of science-based standards to ensure consistent and accurate GHG measurements

Implementing an integrated U.S. GHGMMIS will require a phased approach. Phase I takes advantage of and integrates current and planned GHG observational data, modeling, and quality assurance capabilities from federal and non-federal providers into the GHGMMIS. In Phase I, federal agencies will identify and increase coordination of existing, mature GHG observing, measurement, modeling, and analysis activities and capabilities that, with targeted efforts, could significantly improve GHG information in the near term. These efforts will bring to bear the collective assets and expertise of the federal government, while making more efficient use of taxpayer funds and effectively leveraging non-U.S. government efforts. Phase I also includes activities related to the following:

1. The U.S. Greenhouse Gas Center: Initially led by the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), the National Institute of Standards and Technology (NIST), and the National Oceanic and Atmospheric Administration (NOAA), this center will facilitate coordination across federal and non-federal, domestic, and international entities to integrate and distribute actionable GHG data.
2. An Urban-Scale Prototype of the GHGMMIS Framework: Led by NIST and NOAA, this prototype integrates existing GHG measurement and modeling capabilities into an urban-scale operational GHG monitoring system covering the Baltimore, MD/Washington, DC, and Indianapolis, IN, regions, with potential extension to other areas.
3. Sector-Specific Efforts and Demonstration Projects: These activities—related to agriculture, energy, waste, and natural system emissions and removals—showcase a sample of near-term U.S. government efforts related to GHG measurement and monitoring that support the GHGMMIS framework and objectives.

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[b] Activity-based GHG quantification approaches estimate emissions and removals through the use of data describing levels of activity that produce GHG emissions paired with emissions factors (quantifying emissions per unit of activity), models, or methods specific to an economic sector, technology, and often geography/region.

[c] Atmospheric-based GHG quantification approaches use atmospheric measurements of GHGs and an understanding of atmospheric transport and chemical processes to infer information on GHG fluxes. Surface-, aircraft-, balloon- and space-based observations are combined with analysis and models to transform measurement of atmospheric concentrations into estimates of emissions.

Phase II of the GHGMMIS reflects a future iteration in which demonstrations and planning from Phase I enable a more capable, robust system that addresses data needs more comprehensively than Phase I. Phase II also will reflect a more robust and formalized coordination structure to implement the U.S. GHGMMIS and move towards interoperability between U.S. and global observing systems.

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The Greenhouse Gas Measurement and Monitoring Interagency Working Group

The Greenhouse Gas Measurement and Monitoring Interagency Working Group (GHG IWG) was created in January 2022 to enhance coordination of the measurement, monitoring, reporting, and verification of greenhouse gas (GHG) emissions and removals in support of climate efforts at the local, regional, and national levels. The GHG IWG is co-led by the Office of Management and Budget (OMB), Office of Science and Technology Policy (OSTP), and White House Climate Policy Office (CPO).

In addition to the offices listed above, the GHG IWG includes the following departments and agencies:

- Department of Agriculture (USDA)
- Department of Commerce (DOC)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of the Interior (DOI)
- Department of State (DOS)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)

The GHG IWG created two technical working groups: one focused on measurement and monitoring of GHGs from the agriculture and forest sectors, and a second group focused on developing a broader framework and strategy for advancing GHG measurement and monitoring capabilities. The GHG IWG released two Requests for Information[d] to solicit input on draft strategies. Additionally, members of the GHG IWG met with external stakeholders, including businesses, industry organizations, state agencies, researchers, and non-governmental organizations. The final *National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System* combines the work of the technical working groups and incorporates public feedback received through the stakeholder meetings and Requests for Information.

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[d] The draft *Federal Strategy to Advance an Integrated U.S. Greenhouse Gas Monitoring and Information System* was released February 2023 at https://go.nasa.gov/USGGMIDraftFederalStrategy. The draft *Federal Strategy to Advance Greenhouse Gas Emissions Measurement and Monitoring for the Agriculture and Forest Sectors* was released July 2023 at https://www.regulations.gov/docket/USDA-2023-0009.

I. Introduction

The Need for a National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System

The United States has committed to reduce economy-wide net greenhouse gas (GHG) emissions 50-52% from 2005 levels in 2030 and to reach net-zero emissions by 2050.[1] These national goals are aligned with the global goal under the Paris Agreement to reduce GHG emissions in order to keep the global average temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius above pre-industrial levels.[2] Enhancing the Nation's GHG measurement, monitoring, and modeling capabilities is foundational to achieving these ambitious goals, as it will improve our ability to track progress towards GHG emissions targets and assess the effectiveness of climate policies and actions.

Identifying and quantifying sources of GHG emissions (sources) and removals (sinks) from the United States' economy, lands, and waters is a complex undertaking requiring large amounts of direct and indirect measurements, modeling efforts, and collection of data across a large range of economic sectors and physical systems. Some GHG sources, such as fossil fuel carbon dioxide emissions from power plants, industrial facilities, and other stationary sources, can be estimated with high accuracy.[e] By contrast, quantifying GHGs from other sources, such as from agriculture or natural ecosystem sources and sinks, continues to be challenging. Despite the complexity, capabilities to measure, monitor, and model GHGs are evolving rapidly due to scientific and technological advances. Many of these advancements have been developed by the U.S. research community and supported by U.S. government (USG) investments, enabling the United States to become a leader in GHG research, modeling, and technology development and transparent compilation and reporting of anthropogenic sources of GHG emissions and sinks.

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[e] Federal regulations requiring reporting of emissions data for certain sectors contributes to the utility and availability of data for those sectors, e.g., EPA's Greenhouse Gas Reporting Program requires reporting of GHG emissions and other data for 41 categories of reporters such as power plants, petroleum and natural gas systems, coal mines, and landfills.

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Definitions

GHGs—such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and others—are gaseous constituents of the atmosphere, with both human and natural sources, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. GHGs in the Earth's atmosphere trap heat.[3]

GHG **emissions** (sources) or **removals** (sinks) are any process or activity that releases or removes a GHG, an aerosol, or a precursor of a GHG into the atmosphere. Both emissions and removals are **GHG fluxes** (flows) to and from the atmosphere.

Advances in GHG measurement and monitoring capabilities have coincided with growing demand for trusted, reliable GHG information that can be used by the USG, cities, states, businesses, non-profits, and others to inform climate strategies and policies. These entities may be users or providers of GHG information, or both. Recent years have seen a rise in commercial and philanthropic-sponsored demonstration and operation of GHG measurement networks, satellites, data platforms, and related information services. While a significant amount of GHG measurement and monitoring activity and expertise is spread across the federal and non-federal spaces, there has not previously been a strategy to collectively guide USG, regional, commercial, philanthropic, and academic capabilities to enhance GHG data and information. Additionally, many USG-funded GHG measurement activities were designed to address agency-specific missions and/or short-term research investigations and are not intended to provide the systematic and sustained monitoring and analysis of GHG fluxes needed to meet climate policy goals.

The *National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System* (National Strategy) responds to these opportunities by providing the following:

- A conceptual framework for a U.S. GHG Measurement, Monitoring, and Information System (U.S. GHGMMIS or GHGMMIS).
- A set of national objectives to focus collective GHG efforts for USG and non-USG entities.
- A phased implementation approach that maximizes the use of mature capabilities today, while paving the way for future GHGMMIS advancements.

A nationally coordinated GHGMMIS will strengthen the Nation's climate efforts by providing authoritative GHG information that is more comprehensive, granular in space and time, and responsive to a wide range of user needs for quantifying and tracking GHG emissions and removals. It is well aligned with the USG vision that "every American, every community, and every business has access to usable climate services that empower them to prepare, respond, and be resilient to climate change,"[4] and aims to take advantage of capabilities and GHG data produced by federal, academic, and non-governmental organizations (NGOs); private entities; and state and international governments. Additionally, current GHG measurement and monitoring efforts are spread across multiple federal agencies. Enhancing coordination and integration of agency efforts will help ensure that the USG is making effective use of taxpayer funds and bringing the collective expertise of federal agencies to bear to address national needs.

Existing U.S. Government Efforts as a Foundation for the U.S. GHGMMIS

The National Strategy builds upon a strong foundation of existing USG efforts related to GHG measurement, monitoring, and data provision. The USG contributes a wide array of cooperative research, data products, activities, and capabilities aimed at understanding GHG emissions and removals at various scales and from various sources.

Since the early 1990s, the Environmental Protection Agency (EPA) has compiled the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. GHG Inventory), which fulfills the USG's annual emissions reporting requirement to the United Nations under the Framework Convention on Climate Change (UNFCCC). The U.S. GHG Inventory identifies and quantifies anthropogenic[f] sources and sinks of a wide range of GHGs, for each year starting in 1990, and is the current basis for assessing progress towards achieving the U.S. Nationally Determined Contribution (NDC) under the Paris Agreement. In developing the U.S. GHG Inventory, EPA draws upon the expertise of more than a dozen U.S. government agencies, academic institutions, industry associations, and other organizations. The information developed in the U.S. GHG Inventory provides a good starting point for identifying known capabilities, gaps, and challenges related to measurement and monitoring of anthropogenically generated GHGs. EPA also collects GHG emissions data from over 8,000 individual facilities and suppliers of certain fossil fuels and GHGs through its regulatory Greenhouse Gas Reporting Program (GHGRP). The GHGRP provides facility-level emissions from the largest industrial sources of GHG emissions in the United States.[g]

Other departments and agencies contribute significantly to understanding GHG emissions, both for use in the U.S. GHG Inventory and for advancing the state of knowledge in the field more generally. For example, the U.S. Department of Agriculture (USDA), Department of Commerce (DOC), Department of Energy (DOE), Department of the Interior (DOI), National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF) have made significant investments in carbon cycle research, GHG-relevant surveys, and production of GHG-related data products, as well as advancing GHG measurement, modeling, and analyses.

[f] Emissions or removals that are a direct result of human activities, or a result of natural processes affected by human activity. https://www.epa.gov/system/files/documents/2023-02/US-GHG-Inventory-2023-Main-Text.pdf.

[g] Direct emissions reported to the GHGRP account for about 50% of total U.S. GHG emissions, and data reported to the GHGRP from both direct emitters and upstream suppliers combined cover 85-90% of U.S. GHG emissions.

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Figure 1. *Carbon dioxide (CO_2) data collected at NOAA's Mauna Loa observatory in Hawai'i constitute the longest record of direct measurements of CO_2 in Earth's atmosphere. (Image credit: NOAA)*

Example U.S. Government Efforts That Serve as a Foundation for the U.S. GHGMMIS

- Activity-based data and other data valuable to estimating GHG sources and sinks, including spatially explicit (gridded) products from EPA, USDA, the Energy Information Administration, and other agencies.
- USDA-supported long-term observational networks, such as the Forest Service's Forest Inventory and Analysis (FIA) National Program and the National Resources Inventory (NRI).
- NIST's Urban Testbed program, which has worked with universities, other federal agencies, and the private sector to support GHG measurement testbeds in metropolitan areas that combine atmospheric measurements and analyses to estimate urban GHG emissions.
- NOAA's Global Greenhouse Gas Reference Network, which includes ongoing surface, shipboard, balloon, and aircraft observations. Current observations and data assimilation systems are sufficient to enable regional- to national-scale emissions for the United States for carbon dioxide, methane, nitrous oxide, and the fluorinated gases.
- NOAA-supported modeling capabilities including numerical weather prediction and transport and dispersion models.
- NOAA's near real-time satellite-based fire emissions algorithm that provides estimates of carbon dioxide and methane fluxes from fires on an hourly cadence for North America.

- NASA-funded satellites and instruments, including the Orbiting Carbon Observatories (OCO-2 and OCO-3) and the Earth Surface Mineral Dust Source Investigation (EMIT).
- NASA GHG data assimilation systems and airborne research program, which support urban to regional analyses of fluxes and concentrations.
- NASA's Carbon Monitoring System, which prototypes the development of capabilities necessary to support stakeholder needs for monitoring, reporting, and verification of carbon stocks and fluxes.
- Observation, modeling, and data analysis capabilities as part of research investigations or projects funded by DOE, NASA, NOAA, NSF, the U.S. Geological Survey (USGS), and the Smithsonian Institution.

In 2023, the USG initiated an effort to develop a U.S. Greenhouse Gas Center (U.S. GHG Center) to accelerate the production and delivery of actionable, high-quality GHG information. This nascent effort is being implemented by NASA, EPA, NOAA, and NIST and will potentially include data and tools from other agencies, as well as non-USG entities. The U.S. GHG Center is described in more detail in Sections II and III.

Linkage to International Efforts

While the National Strategy initially focuses on developing a GHGMMIS to address information needs related to U.S. GHG emissions, it also supports enhancements to GHG measurement, monitoring, and information provisioning that will be extensible to international efforts. Several agencies of the GHG IWG have and will continue to play leading roles in international efforts to measure, monitor, and quantify global GHG emissions. EPA, USDA, USGS, NOAA, and other agencies directly support the development and enhancement of internationally-accepted estimation methodologies by the Intergovernmental Panel on Climate Change's (IPCC) Task Force on National Greenhouse Gas Inventories, and various agencies support capacity building for international partners on the use of these methodologies.[5] USG-funded observing systems and programs are providing global GHG atmospheric concentration information and analyses that are openly available to all stakeholders. NASA, NOAA, and NIST have been long-standing supporters of the World Meteorological Organization (WMO) Integrated Global Greenhouse Gas Information System,[6] which aims to provide GHG information on policy- and management-relevant scales and ensures that such information is based on documented research, community best practices, and measurement standards.[7] Both NOAA and NASA are involved in the new WMO Global Greenhouse Gas Watch initiative,[8] which aims to provide sustained, routine global monitoring of GHG concentrations and fluxes. Federal agencies also participate in organizations that have taken an interest in advancing space-based GHG monitoring such as the Committee on Earth Observation Satellites (CEOS),[9] WMO,[10] the Group on Earth Observations,[11] the Coordination Group for Meteorological Satellites,[12] and the Global Forest Observation Initiative.[13] A key goal in such partnerships is to foster consistency and interoperability in methods and data, as well as advance a framework for global GHG measurement and monitoring.

II. An Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System

The U.S. GHGMMIS Vision

The U.S GHGMMIS will quantify GHG emissions and removals to support public and private sector climate efforts in the United States at local, state, Tribal, and national levels. The GHGMMIS will be based upon scientifically validated methods, with sufficient granularity in space and time for acquisition, analysis, and dissemination of trusted, reliable, transparent, and accurate data. The GHGMMIS will be extensible to international efforts on sustained, coordinated global GHG monitoring.

The U.S. GHGMMIS Framework

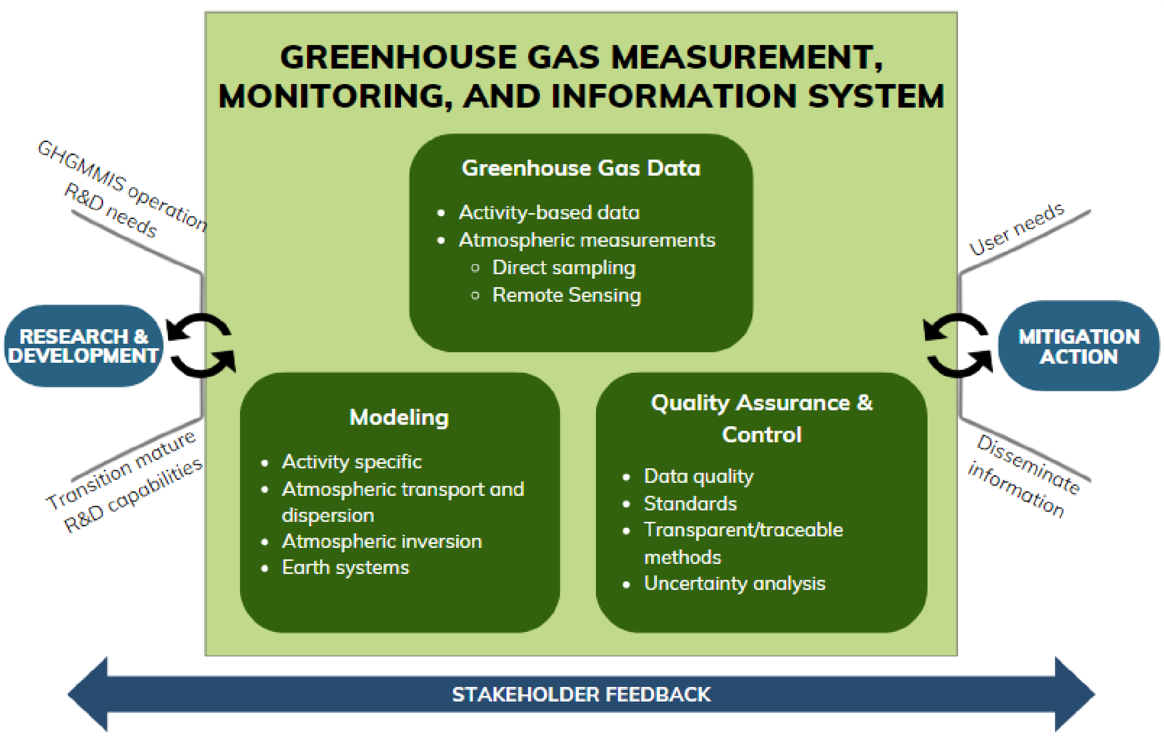

Figure 2. The GHGMMIS will leverage and integrate USG and non-USG measurement, monitoring, and data capabilities and assets—ranging from data and modeling systems to data quality assurance and dissemination.

The U.S. GHG Measurement, Monitoring, and Information System comprises three core components: 1) GHG data derived from activity-level estimates and/or atmospheric measurements; 2) standards and methods for quality assurance and quality control (QA/QC); and 3) modeling efforts (Figure 2). The three core components of the GHGMMIS exist today, though individual activities have differing levels of maturity, and the collective set of capabilities have not been fully optimized as an integrated system. The National Strategy seeks to leverage existing work and accelerate integration of the three components across USG and non-USG into a GHGMMIS that operates in a sustained mode. The GHGMMIS will provide high-quality, actionable GHG information that supports U.S. efforts to meet GHG reduction goals, including GHG tracking, analysis, reporting, and verification. Reliance on a combination of activity- and atmospheric-based approaches for the three core components will enable the GHGMMIS to produce GHG information at multiple temporal and spatial scales, with source- and process-level detail (these approaches are discussed further in the National Objectives for Advancing the U.S. GHGMMIS section).

Research and development (R&D), including research on atmospheric processes, technology development to enhance the accuracy and reliability of GHG sensors, and prototypes demonstrating integrated monitoring systems are key to advancing the GHGMMIS's capabilities and serve as an input into the GHGMMIS. Feedback from work on the core components of the GHGMMIS and its stakeholders, in turn, will inform future R&D.

Numerous technologies, including for monitoring GHG concentrations in the atmosphere and ocean, determining GHG fluxes, and directly measuring emissions, are being developed or have demonstrated capabilities in a research or demonstration setting but have not been fully vetted for more sustained, robust use. The USG will develop processes for identifying mature research capabilities that are ready to transition to the GHGMMIS and for identifying promising research, including measurement technologies and approaches, that should be further developed for potential use in the GHGMMIS.

The GHGMMIS will facilitate development of authoritative, transparent data on GHG emissions and removals, including data that can be further customized by non-USG entities for specific user applications. Engaging with stakeholders to better understand evolving user needs and how the GHGMMIS can meet those needs provides feedback for continuous improvement of all aspects of the GHGMMIS.

Leveraging Activity- and Atmospheric-Based Approaches

Activity-based GHG quantification approaches (sometimes referred to as "bottom-up" approaches or engineering approaches) estimate emissions and removals through the use of data describing levels of activities that produce GHG emissions paired with emissions factors (quantifying emissions per unit of activity), models, or methods specific to an economic sector, technology, and often geography/region.

- Activity data provide detailed information on the level of economic sector activity, e.g., number of cattle or swine, well counts, equipment counts, traffic counts, acres of wetlands converted, and fuel consumption statistics. The activity is usually directly measured but may be derived through other ways in the absence of directly measured data.
- Emissions factors are coefficients—emission rates per unit activity—that allow the conversion of activity levels to estimate GHGs either generated or removed. Emissions factors can be derived from regular or periodic direct measurement and/or chemical relationships in the absence of measured data.

Atmospheric-based approaches for GHG quantification (sometimes referred to as "top-down" approaches) use atmospheric measurements of GHGs and an understanding of atmospheric transport and chemical processes to infer information on GHG fluxes. Surface-, aircraft-, balloon- and space-based observations are combined with analysis and models to transform measurement of atmospheric concentrations into estimates of emissions.

These approaches are discussed further in the National Objectives for Advancing the U.S. GHGMMIS section. Additionally, the National Academies of Sciences, Engineering, and Medicine describe these approaches in detail in their 2022 report, *Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward*.[14]

Principles of the U.S. GHGMMIS

The principles outlined here articulate values needed to maximize the utility, benefit, and credibility of the GHGMMIS itself, its products, and those derived from it. GHGMMIS principles include:

- ***Science-based:*** The GHGMMIS will be based on the best-available science to provide decision-makers and stakeholders with the most reliable, accurate information possible regarding GHGs.
- ***Sustainable:*** The GHGMMIS is intended to operate on a sustained basis. This will require putting in place affordable, sustainable processes and mechanisms for providing consistent, reliable, timely, and robust information over time.

- ***Collaborative:*** The GHGMMIS will help establish and nurture close collaborations between the USG, state/local/Tribal entities, academia, private sector, NGOs, and international institutions in support of the GHGMMIS vision.
- ***Evolving:*** The GHGMMIS will evolve to reflect advances in data, modeling, and measurement technologies, and to include new partners.
- ***Transparent:*** The GHGMMIS will promote transparency in the methods and data used to generate GHG estimates, as well as the quantification of uncertainties associated with those estimates.
- ***Equitable and inclusive:*** Equity and inclusion are core components of stakeholder engagement and operations of the GHGMMIS, with the goal of ensuring products and other benefits are developed inclusively and distributed equitably, including to communities that have not traditionally made use of GHG data and estimation capabilities.

National Objectives for Advancing the U.S. GHGMMIS

As previously stated, GHG measurement, monitoring, and analysis is already taking place through significant efforts by cities, states, businesses, academia, and the USG. Having common national objectives will help focus collective efforts and ensure that agencies are working effectively with each other and with external stakeholders. Therefore, to accelerate improvements, avoid duplication, and maximize use of resources in future GHG quantification efforts, the National Strategy proposes the following cross-cutting objectives:

- Objective 1: Improve Activity-Based GHG Quantification Approaches
- Objective 2: Improve Atmospheric-Based GHG Quantification Approaches
- Objective 3: Coordinate the Use of Activity- and Atmospheric-Based Approaches to Move Towards Convergence of GHG Estimates
- Objective 4: Improve Latency, Completeness, Interoperability, and Accessibility of GHG Data
- Objective 5: Support Development of Science-Based Standards to Ensure Consistent and Accurate GHG Measurements

Efforts to address these objectives will generate benefits across a diverse set of applications. The description of objectives here is purposely high level, to reflect their applicability to a wide range of GHG information needs. More detail on how they will be implemented in specific sector efforts is provided in Section III—Implementing an Integrated U.S. GHG Measurement, Monitoring, and Information System.

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Objective 1: Improve Activity-Based Greenhouse Gas Quantification Approaches

Activity-based GHG quantification approaches (sometimes referred to as "bottom-up" approaches) estimate emissions and removals through use of data describing the level of activities that produce GHG emissions. These data are then paired with models, methods, or emissions factors that are specific to an economic sector and/or technology to produce GHG estimates. Activity-based approaches can also include direct measurement of some sources and processes, and emissions factors themselves are typically the result of measurement and sampling programs.[h] The U.S. GHG Inventory, corporate GHG accounting, and state-level inventories all use activity-based GHG quantification approaches[15,16,17] that form the basis of emissions reduction targets and climate actions.

While activity data paired with default emissions factors from the IPCC's Emissions Factor Database can provide a useful first estimate of emissions or removals, activity-based approaches provide better results when information can be disaggregated into the smallest homogenous sub-groups with rigorous measurements to develop a representative emissions factor for each. For example, in addition to the use of models and facility-level measurements, the U.S. GHG Inventory incorporates country- or region-specific emissions factors for disaggregated equipment types.

The GHGMMIS will benefit from processes used in the U.S. GHG Inventory for improving estimates of anthropogenic GHG emissions. In addition to providing annually updated assessments of uncertainty and areas of improvement for each emissions and removal category, EPA conducts expert and public review periods during which reviewers can recommend improved methodologies, activity data, and emissions factors.[18] Increased interagency collaboration on the Supporting Tasks below has the potential to accelerate improvements to activity data and emissions factors, particularly in areas currently not well characterized, but with large potential for reducing emissions and/or increasing removals. Many local and regional entities, as well as corporations, base their GHG accounting efforts on methodologies, activity data, and emissions factors developed by EPA as part of its annual GHG Inventory process. Thus, improvements to the U.S. GHG Inventory could benefit a broader set of activity-based GHG accounting efforts. Spatially explicit emissions modeling, used extensively by atmospheric-based approaches, described in Objective 2, also benefits from improvement to both activity and emissions factor data.

Supporting Task: Improve activity data, including information on baseline emissions that provide a benchmark for evaluating the impact of climate actions over time.

Federal agencies will work with external partners to improve data and measurements used to derive activity data values. Enhanced activity data in key areas will assist with assessing the current level of emissions and tracking the impacts of policies and measures consistently over

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[h] For example, continuous emissions monitoring at electricity generating units (power plants) and periodic measurement or sampling of process inputs and operating conditions (e.g., carbon or heat content of fuels).

time. Section III—Sector-Specific Efforts and Demonstration Projects—highlights example areas where enhanced activity data would be beneficial.

Efforts to improve activity data impact the accuracy of both baseline emissions estimates and current estimates, thereby improving confidence in both. For example, the U.S. GHG Inventory annually reports emissions and sinks, starting in 1990; any updates to assumptions in the latest GHG Inventory strive to recreate activity levels consistently, at least back to this date. More broadly, there is also a need to establish current baseline estimates of emissions to track activity data consistently over time to assess the effectiveness of climate policies and actions.

Supporting Task: Improve emissions factors.

Emissions factors are key tools in the development of GHG inventories. The accuracy of emissions factors is higher when they are more representative of the underlying source populations, particularly where emissions factors are applied to a subset where the underlying population is more homogenous (e.g., dairy cows vs. all cattle). Emissions factors will also provide better results when they are derived from rigorous measurements under a variety of conditions. EPA, USDA, and other agencies will work with partners to design and implement measurement campaigns to inform updates to emissions factors, including the underlying science and models to improve their accuracy. This includes expanding current efforts to demonstrate measurement capabilities that could inform development of more representative emissions factors, including emissions factors that more accurately reflect seasonal and diurnal variations. Areas where updates of emissions factors could significantly improve inventory estimates include, but are not limited to, livestock, landfills, natural gas systems, flooded lands, and wildfires. Section III—Sector-Specific Efforts and Demonstration Projects—provides more details on efforts related to these areas.

Supporting Task: Develop a USG "living" set of guidance for researchers interested in studies to inform improvements to activity-based GHG estimates.

Although hundreds of studies containing information on GHG emissions and removals in the United States are published each year, few are directly useful for updating or evaluating activity-based GHG estimates, including those in USDA's *Quantifying Greenhouse Gas Fluxes from Agriculture and Forestry: Methods for Entity Scale Inventory report* (Methods report) and the U.S. GHG Inventory. Studies are often not able to attribute emissions to the level at which GHG inventories are calculated (e.g., process and equipment types), definitions may differ making comparisons challenging, studies might not be representative over the spatial and temporal scales needed for bottom-up calculations, or supplementary information on *in situ* conditions may be missing.

Measurement campaigns aimed at improving emissions factor and/or activity parameters should involve experimental design that carefully considers simultaneous determination of values for both. Such data can then be used to improve the performance of bottom-up estimation models. Typically, academic studies do not aim to quantify both the emissions involved and the pertinent onsite activity parameters.

EPA and USDA will lead an effort to develop, disseminate, and routinely update guidance on how studies can be more relevant and usable for inventory improvement efforts. EPA will engage with agencies that fund research to explore opportunities for incorporating these guidelines into future solicitations and outreach to the science community. This effort will accelerate alignment of methodologies developed by the scientific community with those used by inventory developers, as the GHGMMIS moves toward the concept of convergence discussed in Objective 3: Coordinate the Use of Activity- and Atmospheric-Based Approaches to Move Towards Convergence of GHG Estimates.

Supporting Task: Coordinate with the air quality community to measure and model spatially explicit U.S. GHG emissions.

Improving the data products underlying both GHG and air pollutant emissions estimates requires research to evaluate their associated uncertainties. This is a central focus of a research effort led by NIST and NOAA, which will foster collaboration between the air quality and GHG modeling communities. The new initiative, Greenhouse Gas and Air Pollutant Emissions System, combines atmospheric methods, spatially explicit emissions models, and uncertainty methodologies to develop capabilities to map regions where data and modeling improvements will be the most beneficial.

Objective 2: Improve Atmospheric-Based Greenhouse Gas Quantification Approaches

Atmospheric-based approaches for GHG quantification (sometimes referred to as “top-down” approaches) estimate GHG atmospheric concentrations, as well as emissions and removals, using direct observations of atmospheric GHG concentrations (e.g., from ground stations, tall towers, balloons, aircraft, and satellites) and atmospheric transport and dispersion models (ATDMs)[i] that account for the movement of GHGs from the emitting source to the location from which the observations were taken.[j] A main benefit to direct observations of atmospheric GHG concentrations is sensitivity to all GHG sources and sinks. Some measurement technologies can also provide information about the likely origin of emissions through higher spatial resolution or measurements of co-emitted atmospheric trace gases.[k] In many instances, attribution of elevated GHG concentrations to a specific source can be achieved with ancillary data. For example, GHG isotope information can distinguish between biological and fossil fuel sources of carbon dioxide.

[i] Atmospheric Transport Dispersion Models (ATDMs), driven by meteorological phenomena, mainly come from Numerical Weather Prediction model gridded outputs.

[j] Transforming atmospheric concentration data to flux data requires a measure of GHG movement through the atmosphere, particularly through the planetary boundary layer. These are most often achieved with meteorological measurements and atmospheric transport and dispersion models.

[k] Co-emitted gases are gases that are emitted together from a process or source. Isotopes are slightly different versions of a chemical that have a different number of neutrons in their nuclei. Some sources of GHG emissions have a unique mix of co-emitted gases or isotopic signatures such that, when measured at the same time as a greenhouse gas, allow for attribution of a portion of a measured atmospheric change to a particular process.

Agency efforts to improve atmospheric-based data will focus on increasing the accuracy, usefulness, and cost effectiveness of GHG measurement technologies, as well as supporting coordinated use of a variety of observing systems to provide increased coverage while making the most efficient use of resources.

Supporting Task: Improve methodology for transforming atmospheric GHG concentration data from observing systems to emissions fluxes across spatial scales and economic sectors.

ATDMs play a fundamental role in the conversion of observation-based atmospheric concentration data to emissions fluxes. The ability of these models to correctly simulate transport processes directly impacts the quality and accuracy of estimated emissions. Although ATDMs have improved significantly, uncertainties remain, mostly driven by our limited ability to represent near-surface and vertically distributed dispersion processes and turbulent mixing on relevant spatial and temporal scales. This is especially the case for satellite data, where understanding of dispersion and transport processes throughout the atmospheric column is currently limited. In addition, small systematic errors in satellite retrievals[1] can directly contribute to inaccuracies in GHG flux estimates.

Improving the performance of these models, including through reducing uncertainties, requires advances in the understanding of atmospheric transport processes and phenomena, particularly in the planetary boundary layer, and improving numerical weather prediction performance via both modeling advances and expanded meteorological observations. NASA, NOAA, NSF are supporting research to better understand planetary boundary layer processes. NOAA continues to improve performance of ATDMs; the HYSPLIT transport and dispersion model developed by NOAA's Air Resources Laboratory serves as the modeling foundation for the urban-scale prototype of the GHGMMIS discussed in Section III.

[1] Satellite retrievals refers to the process by which spectral radiance data from satellites is used to determine the average concentration of gases in a vertical column unit of the atmosphere.

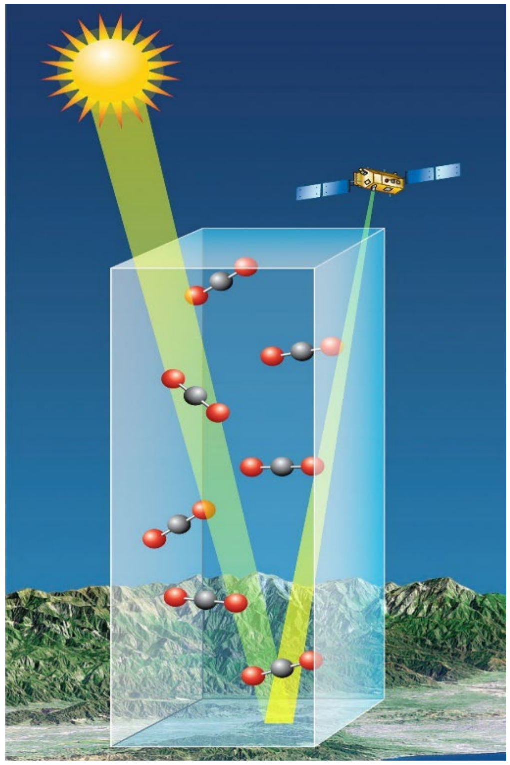

Figure 3. *Satellites do not measure GHG emissions directly. Instead, they measure changes in the intensity of sunlight caused by absorption of GHGs in the air. Further analyses transform these observations into values of atmospheric GHG concentrations, which are combined with atmospheric transport and dispersion models to infer information on GHG emissions and removals. (Image credit: NASA Jet Propulsion Laboratory)*

Supporting Task: Increase capabilities and accuracy of GHG remote sensing.

USG technology investments have led to significant advancements in GHG remote sensing technologies. NASA's Orbiting Carbon Observatory (OCO-2) satellite has produced the most complete global coverage of CO_2 concentrations to date, and OCO-3 has the ability to scan large contiguous areas of emissions hot spots such as cities and power plants. NASA-developed imaging spectrometer technology, most recently demonstrated by the Earth Surface Mineral Dust Source Investigation (EMIT) instrument currently on the International Space Station, is being used to detect methane plumes from "super-emitters." NASA continues to support instrument development, including new optical designs to reduce instrument size, power, and cost, and electronics to increase observations and throughput. In 2024, NASA is expected to initiate mission concept studies for a new GHG satellite mission as part of its Earth System Explorers program.[m]

[m] The Earth System Explorers program funds targeted space-based Earth system science investigations. NASA expects to select four missions for initial mission concept studies in FY 2024.

NOAA polar and geostationary satellites include instruments that measure CO_2 and other trace gases in the atmosphere, can detect very large methane plumes, and support development of wildfire emissions data products.[n] NOAA will continue to collaborate with NASA to explore how current and future satellite capabilities, including from international partners and commercial entities, can be leveraged to support GHG-related applications. Additionally, NOAA and DOI are in the early stages of a collaboration to detect leaks from oil rigs in the Gulf of Mexico.

Validation efforts involving surface and airborne observations will contribute to enhanced understanding and correction of satellite retrievals. Current and upcoming satellite instruments for CO_2 and methane rely on the Total Carbon Column Observing Network (TCCON), related programs including the Collaborative Carbon Column Observing Network (COCCON), and infrequent balloon and aircraft-based vertical profiles for calibration and validation. The TCCON network was initiated by the Orbiting Carbon Observatory projects and advanced with international cooperation among various interested space agencies around the world. NASA, NOAA, and NIST are expected to enhance these networks over the next few years, with a focus on locations with potential systematic uncertainties in satellite retrievals.

NIST research is addressing the need for a next-generation GHG calibration system capable of extending SI traceability[o] to global satellite remote sensing and terrestrial remote sensing platforms across all relevant spatial scales. This will allow direct calibration of GHG remote sensing satellites and will provide the critical methane and carbon dioxide metrology necessary to monitor the natural background and anthropogenic sources globally.[19] Some of these efforts will be coordinated by the U.S GHG Center, which is planning to leverage lower-cost ground-based instruments to complement existing *in situ* sites to expand calibration and validation efforts across the United States.

Lastly, NOAA's Global Greenhouse Gas Reference Network continues to play an important role in providing measurements, which are directly traceable to internationally accepted calibration scales, to identify and correct biases in observing systems such as satellites. NOAA is also leading USG engagement in the WMO's Global Greenhouse Gas Watch program, which aims to create an international GHG reference network that would enable a consistent, sustained global set of observations of GHG concentrations and fluxes.

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[n] NOAA's Global Biomass Burning Emissions Product provides daily burning emissions of CO_2, CO, and particulate matter using fire detection data from NOAA polar satellites. https://www.ospo.noaa.gov/Products/land/gbbepx/.

[o] Traceability of measurement standards to the International System of Units (SI) is established by an unbroken chain of calibrations or comparisons linking them to primary standards of the SI units of measurement.

Supporting Task: Adopt a multi-tiered observing strategy to enhance coverage of GHG fluxes.

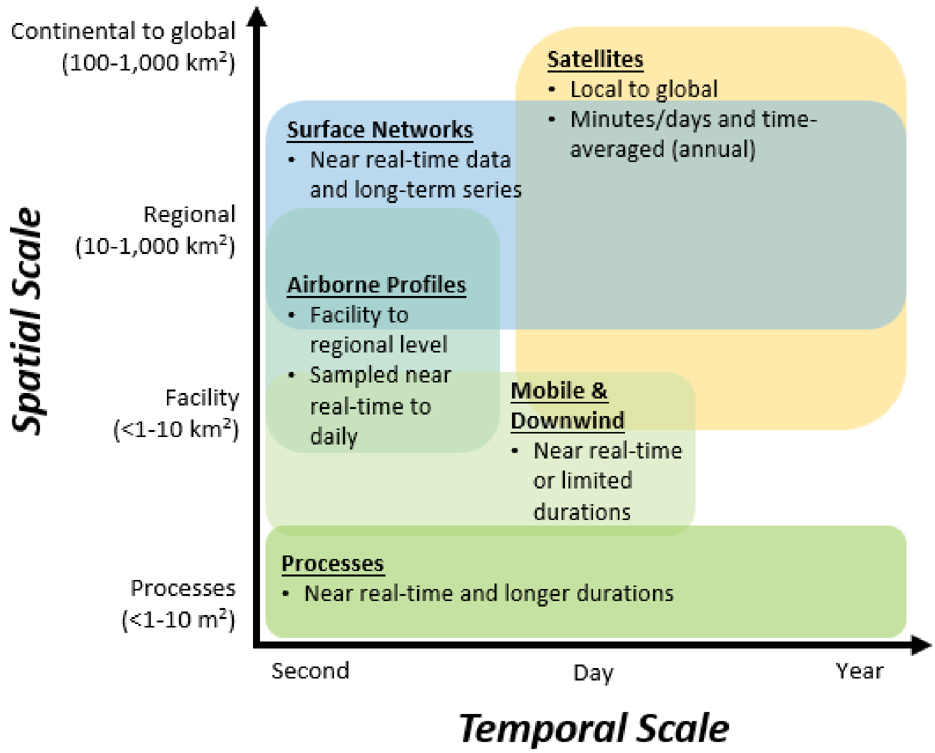

Figure 4. *A multi-tiered observing strategy enables greater coverage across spatial and temporal scales.*

The GHGMMIS emphasizes a multi-tiered observing strategy (Figure 4), in which multiple observing systems (satellite, airborne, and surface networks) are used concurrently to provide more comprehensive spatial and temporal coverage compared to relying on an individual observing assets.[20,21] Use of multiple methods with overlapping capabilities not only improves spatial and temporal coverage, but also allows independent performance assessment among observing technologies, thereby increasing confidence of GHG data and information. For example, the use of surface networks can significantly reduce uncertainties in data from remote sensing instruments mentioned earlier.

Use of multiple observing systems also helps to overcome disadvantages of any one observing system. For example, satellites can only make atmospheric concentration measurements during cloud-free periods and airborne campaigns can become cost prohibitive if expanded to large areas.

Multi-tiered observing strategies are envisioned to become more commonplace as new, high-quality observing systems come online. Importantly, this kind of approach will be crucial in providing information for targeting and prioritization of emissions reduction opportunities and for improving quantification of current emissions and removal trends, as described below in Objective 3—Coordinating the Use of Atmospheric- and Activity-Based Approaches to Move Towards Convergence of GHG Estimates. The GHGMMIS will prioritize comparing and integrating emissions estimates made through these various measurement approaches that are sensitive on different spatial and temporal scales.

Objective 3: Coordinate the Use of Activity- and Atmospheric-Based Approaches to Move Towards Convergence of Greenhouse Gas Estimates

The GHGMMIS will seek to improve GHG information through the combination of atmospheric- and activity-based approaches. Because both approaches have strengths and limitations, comparisons of emissions estimates based on atmospheric observations and modeling techniques with activity-based emissions estimates can identify opportunities for improvement in both datasets.

Activity-Based (Bottom-Up) Approaches

Strengths:

- Robust infrastructure for national-level emissions reporting already exists, with varying maturity of inventories at state, local, and corporate levels.
- Allows attribution of emissions to sources.
- Highly accurate at various scales for fossil fuel carbon dioxide emissions if high-quality energy statistics are available.

Limitations:

- Excludes some emissions sources and sinks.
- Measured activity data and/or emissions factors for some sources may not accurately represent the full range of emitters they are applied to.
- Emissions factors may need to be updated periodically, as necessary, to reflect the emissions benefits of conservation practices (e.g., to assess if average methane emissions per ruminant animal are changing as feed additives are adopted).

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Atmospheric-Based (Top-Down) Approaches

Strengths:

- Sensitive to atmospheric concentrations of all emissions sources and sinks, including natural sources.
- Global coverage with satellites.
- Increasing availability of atmospheric measurements as non-USG data providers come online in the next few years.
- Can be used to identify additional opportunities for efficiencies and mitigation (e.g., identification of large methane leaks).

Limitations:

- Uncertainties in modeling used to transform GHG concentration data to emissions fluxes.
- Cannot attribute atmospheric concentration data to source of emitted emissions without ancillary data.
- Observing systems can be expensive to develop and maintain.
- Satellite measurements are limited by clouds; ground-based measurements are limited by extent of coverage.
- No current methods exist to extrapolate data back in time (prior to measurements taking place) to develop a consistent, long-term time series.

For sources and sinks where existing emissions estimates have higher uncertainties,[p] achieving convergence of results from both approaches is expected to be an iterative process that will lead to improvements in the consistency, accuracy, and specificity of GHG estimates.

The research and emissions reporting communities have demonstrated success with comparing activity- and atmospheric-based methods. These studies generally compare atmospheric results with spatially explicit, activity-based datasets from local[22,23,24] to national[25,26] scales. However, these research methods, models, and products may lack the robustness, completeness, and frequency of updates for routine, coordinated use of atmospheric- and activity- based approaches. As various analytical and observational capabilities evolve, use of atmospheric approaches in concert with activity-based approaches is expected to become more practical, though significant effort would still be needed to transition research-grade models and data products to more robust, sustained capabilities.

[p] Where uncertainties are considered to be composed of both randomly distributed and systematic components.

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A Potential Model for Collaboration Between Atmospheric Scientists and Inventory Developers

Sulfur hexafluoride (SF_6) is the most potent GHG known and has been used in electrical circuit breakers and high-voltage gas-insulated switchgear in electric power transmission and distribution equipment. In 2023, researchers developed atmospheric-based emissions estimates of SF_6 from the United States based on inverse modeling of observational data from NOAA's Global Greenhouse Gas Reference Network. These results were then used to assess and reconcile differences between emissions estimated through atmosphere-based approaches and those in inventories, leading to identification of areas of improvement for both approaches.[27] This collaboration between atmospheric scientists and EPA's inventory developers, which has also led to improved emissions estimates for hydrofluorocarbons, serves as a potential model for future collaboration on other GHGs between these communities.

Objective 4: Improve Latency, Completeness, Interoperability and Accessibility of Greenhouse Gas Data

Generation of GHG data is supported by multiple agencies, and in many cases these data are stored in different repositories, disseminated in different formats, collected at irregular schedules, and not interoperable with other datasets that could be useful to compare to or combine to provide enhanced data products. Moreover, government-funded research efforts have not typically focused on data attributes desired by non-academic users of GHG information, often because research projects or networks are funded to support individual agency missions or inquiry-based research questions.[q] Consequently, the data are not easily accessible beyond the user community that the system was designed to serve.

Agencies, in collaboration with external partners, will focus on areas where improving the latency, completeness, interoperability, and accessibility of current data products can better support climate actions and other stakeholder needs. Agencies will ensure that data products are consistent with the FAIRER (Findable, Accessible, Interoperable, Reusable, Equitable, and Responsible) principles and aligned with agency efforts to advance open science to expand accessibility to data and knowledge generated by publicly funded scientific research.

Supporting Task: Develop a GHG data portal that will provide access to GHG datasets and visualizations.

The U.S. GHG Center (discussed further in Section III—Implementing an Integrated U.S. GHG Measurement, Monitoring, and Information System) will develop an open access, online portal that will provide policymakers and the public with a wide array of GHG datasets and

[q] Examples of current research efforts include NASA-funded research satellites to support science objectives identified by the Earth science community and NASA's core mission to "explore the unknown in air and space" by increasing understanding of Earth systems science from space. NSF funds investigator-driven project proposals. USGS science and research support the missions of DOI bureaus.

visualizations, with the goal of providing data products to users on a regular basis and enabled by advanced science-based capabilities. Initial datasets that will be available on the portal include regularly updated, spatially resolved gridded methane emissions data; data on natural GHG emissions and removals; and data on large methane leak events leveraging aircraft and satellite data. Development of the data portal is expected to be an iterative process, with initial datasets reflecting a limited set of use cases for which relatively mature data products already exist, and future datasets expected to be more responsive to stakeholder needs, which will be solicited over the upcoming year. Additionally, while initial datasets will derive from USG observing and modeling systems, the U.S. GHG Center also plans to disseminate non-USG data through its portal.

Supporting Task: Develop a plan for implementing sustained stakeholder engagement to provide routine feedback to inform GHGMMIS implementation, including refinement of GHGMMIS data products.

Stakeholders of the GHGMMIS are far ranging[r] and include both users and providers of GHG data from inside and outside the USG. Based on preliminary discussions and outreach, stakeholders have expressed a desire for clear mechanisms and avenues for sustained, meaningful engagement with the USG during the implementation of the GHGMMIS, clarification of agency roles and responsibilities to facilitate more direct external outreach with agencies on specific issues, and use of intermediary (boundary) organizations that can facilitate collaboration between researchers and users of GHG data.

The U.S. GHG Center is developing a stakeholder engagement strategy to extend user and stakeholder engagement, including through consultations, workshops, and technical meetings. The feedback received via the various stakeholder engagement activities will be collected in a stakeholder needs catalog and event reports that will be mined periodically for ideas on new capabilities and enhancements to the U.S. GHG Center and the GHGMMIS. Training webinars and workshops will detail the steps toward data access, analysis and visualization, and utilization of the knowledge resources provided by the U.S. GHG Center. To promote sustained engagement, the U.S. GHG Center is developing a user working group that will provide assessments of existing products and feedback on the extent to which these products reflect user needs. To the extent possible, the user working group will include representatives from all sectors of the user communities that are serviced by the U.S. GHG Center products and services.

Objective 5: Support Development of Science-Based Standards to Ensure Consistent and Accurate Greenhouse Gas Measurements

Standards development, dissemination, and adoption will play a critical role in improving the accuracy and consistency of GHG measurements across observing instruments, methods, and data providers. The standards discussed in this objective refer to physical and documentary standards that specify protocols, methods, and use of specific physical standards.

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[r] Stakeholders include local, state, and Tribal governments; regional coordinating bodies; private sector entities; the science community; and international and nongovernmental bodies.

Both types of standards constitute an important USG role that drives confidence in data, benefiting the larger GHGMMIS and the public. Engagement on standards is conducted through well-established dissemination processes and organizations, such as the Metre Convention[28] and the WMO.

Additionally, the USG is engaging with the international Earth observing satellite community to enhance global consistency in data and observational protocols for satellite platforms. NASA and NOAA participate in the CEOS, a multidisciplinary, space-based Earth observations organization coordinating international Earth observation efforts. Accuracy and consistency in remote sensing observations and data are supported through CEOS's Calibration & Validation efforts, which include extensive standardization practices. Similarly, NOAA and NASA participate in the Coordination Group for Meteorological Satellites, which focuses on operational remote sensing, and the Global Space-based Inter-Calibration System, an international effort to monitor, improve, and harmonize the quality of observations from operational weather and environmental satellites.

NIST and NOAA Roles in Developing GHG Concentration Measurement Standards

NIST and NOAA have played a critical role in standards development and calibration of GHG sensors, benefiting domestic and international GHG monitoring and measurement efforts. GHG concentration measurement standards take the form of high-pressure gas mixtures having assigned GHG concentration values covering the range of atmospheric GHG concentrations. NIST and NOAA develop suites of primary gas standard mixtures (PSMs) for key GHGs that provide traceability to the International System of Units (SI). Standard Reference Materials, certified to the PSMs, are developed and disseminated to researchers and scientists to achieve consistency in their atmospheric measurements through SI traceability. NIST and NOAA compare their primary standards among themselves and the international gas metrology community to ensure GHG concentration measurement traceability both nationally and internationally.

GHG concentration standards are established and disseminated by NOAA's Global Monitoring Laboratory (GML), which serves as the WMO's Central Calibration Laboratory for carbon dioxide, methane, and nitrous oxide. These standards support surface networks, aircraft, and satellite measurements, which are critical for tracking GHG sources and sinks around the world. NIST collaborates closely with NOAA's GML to provide linkage of the scales to the SI, bolstering international recognition of these standards.

Supporting Task: Increase availability of GHG concentration standards.

Physical standards for GHG measurement are known as GHG concentration standards and take the form of mixtures contained in high-pressure compressed gas metal cylinders that are used to calibrate instruments.

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High-accuracy GHG concentration standards are needed to demonstrate traceability of GHG concentration measuring instruments and their data. However, their availability is a challenge due to limited manufacturing and GHG concentration certification capacity of NOAA, NIST, and within the international metrology community. Demand for high-accuracy GHG concentration standards is expected to increase significantly in the coming decade as observing capabilities expand. Currently an international standards group, led by NIST under Metre Convention structures[s] and including NOAA participation, is addressing this issue. A framework is under development with the objective of more efficiently disseminating larger numbers of GHG concentration standards with the required accuracy and traceability. The framework could likely utilize private sector production capabilities similar to those used widely for air quality gas measurement to augment USG capacity. An example of such a partnership is the NIST Traceable Reference Materials program, a collaboration between NIST and the specialty gas industry that provides quality control to ensure that concentration measurements of power plant continuous emissions monitoring installations meet EPA's air quality and GHG reporting requirements. Realization of an expanded capability will require NIST and NOAA to work with potential higher volume suppliers to meet the anticipated need for GHG concentration standards of requisite accuracy and traceability to U.S. national measurement standards. An expanded program may utilize conformity assessment and laboratory accreditation methods to ensure data consistency and methodology compliance. NIST has existing programs that support evaluation of accreditation bodies and ensure adherence to standards specified in international agreements.[29]

Supporting Task: Support development of documentary standards for GHG Measurements.

Documentary standards[t] are fundamental to achieving GHGMMIS data accuracy, consistency, transparency, and recognition internationally of the methodologies used to produce its data. Documentary standards are created through the consensus development process[30] and often take the form of detailed descriptions of measurement methods and protocols. Many of these involve recognition of measurement references that are physical artifacts—for example, spectral reference data tied to high-pressure gas mixture standards that are foundational to atmospheric GHG concentration measurements of both remote sensing and surface networks. These consensus standards are promulgated in the United States by the American National Standards Institute (ANSI),[31] which is the sole U.S. representative to the International Organization for Standardization (ISO), thereby giving U.S. interests a voice in international standards.

NIST has initiated a documentary standards effort to advance the implementation of mature, measurements-based scientific tools and methods. Specifically, NIST has begun establishing a U.S. presence in the ISO standardization process via ANSI for GHG emissions measurement methods, with the intent of utilizing best practices[32] developed in part by WMO's Integrated Global Greenhouse Gas Information System and Global Atmospheric Watch programs. These

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[s] The Metre Convention has established technical committees to address consistency and accuracy of national measurement standards. Task groups address specific standards issues of the parent consultative committee. https://www.bipm.org/en/committees/cc/ccqm/wg/CCQM-GAWG-TG-GHG.

[t] Documentary standards can specify definition of terms; classifications of components; delineation of procedures; specification of dimensions, materials, processes, products, systems, services, or practices; test methods and sampling procedures; or descriptions of fit.

standards will support existing GHG emissions management standards, including ISO 14064, which describes specifications and guidance at the organization level for quantification and reporting of GHG emissions and removals, and ISO 14065, which provides a quality assurance framework for third-party validation and verification bodies.

Supporting Task: Develop a framework for evaluating and validating non-USG data.

As new sources of data become available, a common, transparent framework for evaluating and validating non-USG data will help ensure that the data meet QA/QC standards. Such a framework can build upon existing processes, such as those used by NASA's Commercial Smallsat Data Acquisition Program to assess new data and a CEOS effort on methods for evaluating commercial data products. Development of the framework will require significant engagement with data users and possibly a tiered approach that recognizes that while some standards may be applicable for all applications, others may vary depending on the applications for which the data will be used. In 2024, the GHG IWG will convene agencies with relevant expertise and potential data users to discuss and develop an initial common USG framework that is broadly applicable.

III. Implementing an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System

The USG will use a phased approach in implementing the National Strategy—supporting near-term activities that enhance GHG information while putting in place plans and capabilities for future enhancements to the GHGMMIS. Phase I takes advantage of, and integrates, current and planned GHG observational data, modeling, and QA/QC capabilities from federal and non-federal providers into the GHGMMIS and begins planning for Phase II. Phase II will largely focus on assessing unfulfilled measurement, monitoring, and data needs, as well as identifying high-priority research or activities needed to mature capabilities for a sustained GHGMMIS.

Phase I

In Phase I, agencies will identify mature GHG observing, measurement, modeling, analysis activities and capabilities that, with targeted efforts, could be transitioned to sustained use to improve GHG information in the near term. Phase I efforts will rely on a combination of federal, non-profit, academic, commercial, state/local, and international capabilities and systems, seeking to strengthen coordination and efficiently use resources. Phase I includes efforts to develop a multi-agency U.S. GHG Center, which will integrate and disseminate mature federal and non-federal GHG information to a variety of users, and the implementation of an urban-scale prototype GHGMMIS. Agencies have already started implementing many of the activities and objectives mentioned in the National Strategy. Key ongoing and planned demonstration projects and research areas to support the GHGMMIS are highlighted later in this section under Sector-Specific Efforts and Demonstration Projects. Additionally, agencies will continue to support and design demonstration projects and support R&D that aligns with the framework and principles of the U.S. GHGMMIS.

Significant USG collaboration with non-federal entities on GHG measurement and monitoring already exists, but the National Strategy recognizes that a clearer framework and mechanism for identifying and collaborating with non-federal entities is needed. It is expected that the U.S. GHGMMIS will leverage the following non-federal capabilities:

Academia/Science Community

- Research, modeling, analysis, measurement expertise and systems from universities and other scientific organizations, including those funded by federal agencies such as NSF, NOAA, NASA, DOI, and DOE.

Industry and NGOs

- Current and upcoming commercial remote sensing data sources that have been evaluated by the USG for requisite data quality.
- Data analytics, dashboards, and other reporting mechanisms for specific user groups.
- Research to advance measurement technologies and methods.

State/Local Governments

- State agencies are sponsoring GHG inventory development and GHG measurement campaigns and capabilities in support of state climate goals. The GHGMMIS will explore how to better partner with states to integrate data, expertise, and knowledge.

International Organizations and Forums

- Satellites like the European Sentinel-5P TROPOMI mission provide high-quality GHG observations. Next-generation government-funded satellites (e.g., Japanese Aerospace Exploration Agency's GOSAT-GW mission, European Space Agency's CO_2M mission[u]) will provide higher spatial resolution, more complete coverage, and more frequent observations.
- Collaboration with other space agencies on cross-calibration and validation efforts against common standards (e.g., the Total Carbon Column Observing Network and airborne profiles).
- Collaboration on calibration and validation methods for methane super-emitters.
- Collaboration with international efforts such as the WMO's Global Greenhouse Gas Watch and Integrated Global Greenhouse Gas Information System, FLUXNET, and the International Methane Emissions Observatory to support GHG monitoring and transparency in GHG data.

The U.S. Greenhouse Gas Center

The U.S. GHG Center, initially led by NASA, EPA, NIST, and NOAA, will facilitate coordination across federal and non-federal, domestic, and international entities to integrate and enhance GHG data and modeling capabilities from the USG and non-USG sources for scalable impact. The GHG Center will integrate GHG information from facility to global scales and leverage data from federal agencies, international and scientific partners, and commercial providers. These data can provide unique, multi-scale GHG information that is valuable for both research and applications. An initial interagency data portal for the GHG Center will be launched in early December at earth.gov/ghgcenter.

In Phase I, the GHG Center will focus on a limited set of use cases that will drive initial collaborations. These initial use cases provide the opportunity to develop best practices and

[u] The Japanese Global Observing SATellite for Greenhouse gases and Water (GOSAT-GW) cycle will launch in 2024. The Copernicus Carbon Dioxide Monitoring (CO_2M) mission, part of Europe's Copernicus Sentinel Expansion missions, will launch in 2025.

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procedures for refining and disseminating information with datasets and modeling capabilities that federal agencies understand well, providing a foundation for future efforts on other use cases. Given the limited number of commercial satellite data providers currently available, initial efforts will primarily leverage USG data while exploring opportunities for future partnerships with non-USG data providers. The GHG Center will also engage with non-governmental entities that may prefer to maintain their own data services and visualization capabilities, to understand their needs and demonstrate interoperability of GHG Center datasets that can help them support evaluation and uncertainty quantification.

U.S. Greenhouse Gas Center Strategic Goals

1. Accelerate GHG monitoring, measurement, reporting, and verification decision support, connecting technology, tools, and data.
2. Foster collaboration with networks of interagency, intergovernmental, and private sector partners to co-develop and increase adoption of impactful applications.
3. Promote scientific innovation and transparency by leveraging advanced data systems capabilities and open-source science principles.
4. Develop products and services needed by users, updated on a regular basis, and enabled by advanced science-based capabilities.
5. Establish bidirectional knowledge transfer and engagement with federal, state, local and Tribal governments; researchers; and the public.
6. Integrate diversity, equity, and inclusion in the Center's research, knowledge transfer, community engagement, management, and operations functions.

Urban-Scale Prototype of the U.S. GHGMMIS Framework

Agencies are currently implementing a prototype of the U.S. GHGMMIS framework on a smaller scale within which various components of the GHGMMIS can be integrated and tested. Led by NIST and NOAA, this prototype integrates existing, mature capabilities across various data providers and modeling capabilities into an urban-scale operational GHG monitoring system covering the Baltimore, MD/Washington, DC, and Indianapolis, IN regions, with potential extension to other areas. The prototype aims to address stakeholder needs for more current and up-to-date GHG information where needed to implement and assess specific GHG reduction strategies while addressing research-to-operations challenges using testbeds with different emissions and meteorological profiles.

The urban-scale prototype GHGMMIS seeks to significantly improve data latency of GHG emissions and removals data compared to the current several-years latency. This allows for investigation and demonstration of a testing framework to transition research-grade models and data products toward more robust, sustained operation. The prototype will combine atmospheric and activity-based methods for whole and sub-city emissions and establish collaborations between regional and local planners and federal agencies to co-develop GHG emissions information data products. It will take advantage of surface-, airborne-, and satellite-based data; activity-based, spatially explicit, fossil fuel carbon dioxide and methane emissions data; and modeling of emissions from urban areas. The prototype will provide lessons learned to inform efforts to scale the GHGMMIS and provide enhanced GHG information for urban and regional stakeholders.

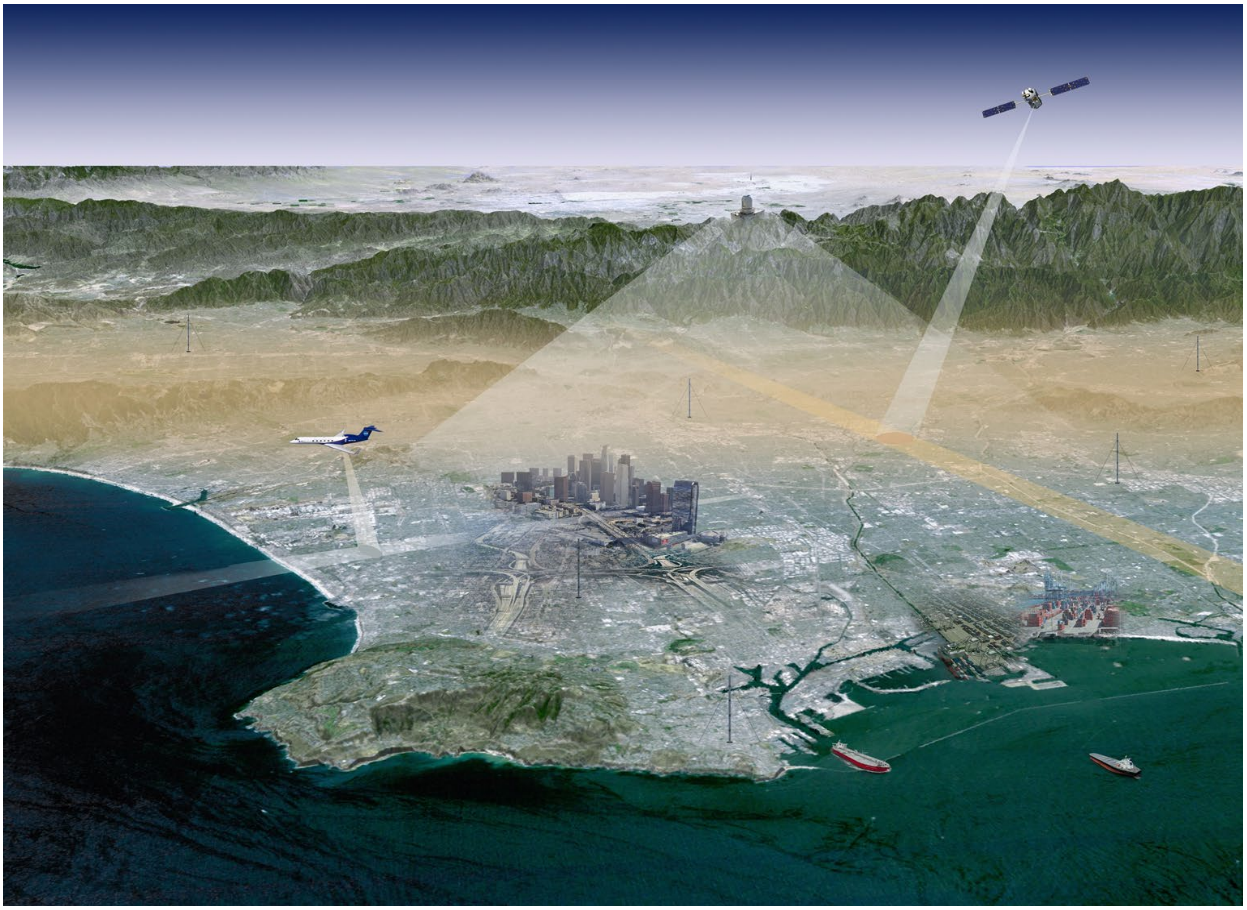

Figure 5. *The urban-scale prototype of the U.S. GHGMMIS framework will focus on integrating capabilities to support sustained GHG monitoring and measurement starting at urban scales, then expanding to regional and national scales. (Image Credit: NASA Jet Propulsion Laboratory)*

Sector-Specific Efforts and Demonstration Projects

The activities highlighted in the following sections—related to agriculture, energy, waste, and natural system fluxes—showcase near-term USG efforts related to GHG measurement and monitoring that support the GHGMMIS framework and objectives. The demonstration areas and projects are not comprehensive of all USG GHG efforts but reflect areas where there is significant interagency interest and where targeted efforts can significantly improve GHG measurement and monitoring capabilities. Some of the sector-specific efforts focus on methane detection and quantification, recognizing significant interest and opportunities at the state and federal levels to reduce methane emissions, and are consistent with the goals of the U.S. Methane Emissions Reduction Action Plan.[33]

Agriculture

In the United States, the agriculture sector contributes roughly 10% of total anthropogenic GHG emissions.[34] The largest agricultural sources of GHG emissions are nitrous oxide emissions from the management of agricultural soils and methane emissions from enteric fermentation and manure management, while soils can serve as a carbon sink. Many of the source and sink categories within the sector are complex and heterogeneous, making GHG quantification challenging. Sophisticated process models are better able to characterize the complexity of these systems compared to emissions factors (e.g., for soil carbon and soil nitrogen). The quality of model results is constrained by limited physical measurements, model uncertainties and biases, lack of data interoperability, and incomplete information on extent and impact of cropland and livestock management practices that influence GHG sources and sinks.

The GHGMMIS envisions integrated measurement, monitoring, reporting, and verification (MMRV) capabilities within the agriculture sector that enable more accurate estimation of entity-, program-, and national-scale emissions and removals. These capabilities provide a means to evaluate impacts of agricultural management practices. Improving our ability to estimate GHG fluxes from agriculture will require a multipronged approach to advance and improve the science, data, and measurement and modeling tools. Strategic priorities for advancing GHG estimates in the agricultural sector include the following:

- Prioritizing investments in research and monitoring that improve understanding of GHG emissions and sinks in response to changes in inputs, management activities, and environmental factors.
- Reducing uncertainty and improving accuracy of measurements, including remote sensing methods, models, and tools that are used to quantify and estimate GHGs from livestock and agricultural soils.
- Improving activity data (e.g., tillage data, animal feed data), environmental data (e.g., soils data, evapotranspiration data), land use/land cover data, hazards data (e.g., pests, wildfire), and other data used to quantify GHG sources and sinks.
- Accelerating integration of improved science, models, and data into GHG estimates for the agriculture sector.
- Using improved GHG estimates to improve the ability to understand the impacts of strategies implemented by landowners and managers, both at the entity scale and in aggregate.

These strategic priorities will improve the accuracy and reduce uncertainty in GHG estimates and improve public trust in them. Availability of significant new climate-smart agriculture funding from the Inflation Reduction Act (IRA) and the Partnerships for Climate-Smart

Commodities program, passage of the bipartisan Growing Climate Solutions Act, new technology and innovations, and robust interest from farmers and ranchers in implementing climate-smart agriculture practices present an opportunity to enhance GHG estimates in the sector and make available the vast data resources of the USG to facilitate MMRV activities across all scales. The IRA has provided $300 million to support USDA's GHG MMRV efforts, providing resources to support research that informs and advances agricultural GHG models, tools, and data products and enhances data management and systems. These IRA investments will help improve accuracy of GHG estimates and enable more efficient targeting of resources within the agriculture sector. USDA's implementation plans are aligned with, and will continue to build from, the goals and objectives set out in the GHGMMIS, working closely with interagency partners and external collaborators.

Animal Agriculture

Implementing agencies include: USDA

Enteric fermentation and livestock manure management are the largest sources of GHG emissions from animal agriculture and are significant sources of methane in the United States.[35] In addition, nitrous oxide emissions from both housing and manure storage can comprise a significant portion of the farm-level GHG footprint. Currently, there are data and research gaps related to estimating GHG emissions from enteric fermentation and manure handling and storage facilities. Needs for improving livestock GHG estimates include filling gaps in activity data (e.g., livestock diet data) and emissions factors used to calculate GHG inventories, advancing research to understand the mechanisms that drive methane and nitrous oxide emissions, and improving models and tools used to estimate methane and nitrous oxide emissions due to changes in management practices or activities.

Supporting Task: Advance critical research to improve model estimates of management interventions that directly reduce enteric fermentation methane emissions.

USDA's Agricultural Research Service (ARS) will advance and accelerate research to measure enteric fermentation methane emissions directly[v] from beef and dairy cattle at different life stages, with the goal of improving model estimates for voluntary management interventions that can reduce GHG emissions. Research findings and data will be used to verify model estimates with real systems data, improve model calibration, refine model equations, and incorporate existing interventions into models. The research data collected for improving model estimates will also lead to an improved understanding of interventions on GHG emissions that can refine and inform management on the farm. The initial research focus will be on the major production enterprises in the industry: beef cattle emissions from both feedlots and grazing production and dairy cattle emissions from both confined housing and grazing production. Cattle production (beef and dairy) in confined production areas offers a greater opportunity to expand and refine management interventions such as diet formulations and feed additives. For beef and dairy cattle on confined feedlots, emissions and management interventions to be evaluated for improving

[v] In contrast to traditional ARS research areas that focus on improving productivity and efficiency of cattle production, which can ultimately reduce enteric fermentation methane emissions per unit of meat and milk product.

model estimates include different forage sources,[w] feed additives and diet ingredients,[x] the effect of diet in beef feedlot systems,[y] and the influence of maternal cow management on physiology and emissions of their offspring calves.[z] For grazing beef and dairy cattle production, management interventions focus on activities that incentivize cattle to eat as high quality of forage as possible[aa] and genetically select for cattle with lower emissions rates.

Research will be conducted in controlled research facilities across six ARS research locations, rather than on farms, using open and closed automatic head-chamber systems, respiration chambers, and environmental chambers to directly detect gas fluxes in ruminant systems.[bb] In vitro lab experiments will be conducted to screen possible feed additives for their potential to reduce methane emissions with the most promising additives elevated to in vivo feeding trials, dependent on funds and availability of experimental cattle. Data collected using innovative sensors in research farm settings as well as data collected through controlled research experiments will help improve models and emissions factors that are used to estimate enteric emissions at the national and farm scales.

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[w] USDA is testing particular forages that agronomically improve soil carbon sequestration or forage products that are typically considered waste stream or by-products in order to support whole-farm GHG reductions. Practices for beef cattle may include but are not limited to feeding cotton by-product roughages as opposed to traditional roughage sources. Practices for dairy cattle may include, but are not limited to, researching the impact of forage processing, cover crop feeding or varying alfalfa and grass silage rations in early and peak lactation.

[x] Feed additives for beef cattle may include but are not limited to phase feeding additional fat, steam-flaked corn with steam-flaked sorghum, cashew nut-shell liquid, zeolite clay minerals, and *Asparagopsis* seaweed. USDA is also exploring the additive effects of feeding multiple of the most promising additives. Feed additives for dairy cattle may include but are not limited to *Garcilaria* red algae and biochar.

[y] Practices may include but are not limited to assessing the impact of rate of gain on enteric fermentation methane production during finishing of beef steer.

[z] Practices may include but are not limited to assessing the impact of maternal dietary energy levels in late lactation and the impact of maternal housing management (pasture or confinement).

[aa] Research for grazing beef cattle may include but is not limited to examining the influence of ecological sites and their seasonal diet quality of forage, influence of improved forages vs. native plant communities, and influence of virtual fences to increase access to high forage quality for livestock during the grazing season. Research for grazing dairy cattle may include but is not limited to understanding the effect of pasture plant composition and management on emissions and the impact of stocking rate strategies on forage nutritive value and animal production and emissions as well as evaluating the impact of novel forage species that can be grown or used in grazing systems.

[bb] The ARS research stations are located in Madison, WI; Bushland, TX; Clay Center, NE; Fort Collins, CO; and El Reno and Woodward, OK. Enteric fermentation emissions monitoring from cattle requires specialized equipment and an ability to monitor individual animals in a controlled setting. Currently, use of this type of equipment and monitoring on production farms is not practical in a commercial setting and would not provide the data needed to evaluate the ability of management to reduce emissions and improve models.

Figure 6. When ruminant animals such as cows digest their food, it gets processed in their systems by way of fermentation. This process breaks the food down over time and produces methane.

Supporting Task: Improve measurement of methane and nitrous oxide emissions from manure handling and storage facilities on livestock farms.

USDA is leveraging its authority under a variety of existing programs to encourage farmers and ranchers to install or upgrade equipment and/or adopt new practices that improve manure management and animal housing practices that can substantially reduce methane emissions in a way that also advances environmental justice. USDA, through the National Resources Conservation Service and ARS, in collaboration with industry groups and the scientific community, have developed a short list of on-farm management practices to evaluate solid separation, lagoon/slurry tank covers, composting, aeration, acidification, feed management, and pen management. These seven practices have shown the potential to reduce GHG emissions on livestock farms and have a high likelihood of being adopted by producers. Consideration will also be paid to better understand how manure management practices will reduce GHG emissions, as some practices may instead shift methane emissions to nitrous oxide emissions, or vice versa.

USDA plans to conduct research on the GHG impacts of the seven voluntary farm management practices at commercial farms as well as large demonstration sites. Research will be coordinated from approximately six ARS research locations[cc] and will leverage university partners to help carry out the research. Research sites were chosen to represent the major U.S. dairy and swine

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[cc] The ARS research stations are located in Kimberly, ID; Ames, IA; Marshfield, WI; Clay Center, NE; Bushland, TX; and Fayetteville, AR.

regions and either have facilities as part of the research location or have strong industry partners to enable access to commercial farms on which to carry out the research. This will enable USDA to evaluate practices in different regions with different climatic conditions. Some of the selected sites are also participating in USDA's Partnerships for Climate Smart Commodities program, allowing USDA to leverage the MMRV activities at these sites. In addition, USDA selected sites that have previously performed similar research as they have the necessary technical background to complete the work.

Several methodologies will be used to measure GHG emissions; however, exact protocols and experiment designs are still being developed and will likely be determined on a case-by-case basis to be site and condition specific. Methodologies to evaluate the GHG benefit of specific management practices include inverse dispersion modeling, tracer gas techniques, and direct measurement via ventilation rate and concentration data (enclosed barns). To understand the impact of management activities, facility-level measurement and monitoring of emissions is needed to compare the variability of emissions between farms and to identify potential management practices that are driving these variations. Inverse dispersion modeling, for example, allows for the determination of emissions continuously without disturbing or altering the source monitored by installing sensors up- and downwind in the prevailing wind direction from the site. This type of modeling will likely be used at sites where conditions are conducive to this type of monitoring. If the farm configuration does not lend itself to inverse dispersion modeling, then established tracer gas methods or other micrometeorological methods may be employed. Other measurement techniques include the use of mobile vans to make short term measurements at a larger number of livestock facilities to better characterize farm-to-farm variability in emissions.

Research findings and resulting model improvements will benefit national, regional, and field-scale quantification efforts, including improving livestock methane and nitrous oxide estimates compiled for the U.S. GHG Inventory, and for improving field-scale tools and methods used to estimate livestock emissions at the field or operation scale.

Agricultural Soils

Implementing agencies include: USDA

Soil carbon gains and losses are generally estimated by measuring changes in soil carbon stocks through a combination of in field (soil) measurements and modeling. The eddy covariance technique allows estimation of carbon gains and losses, measuring at the field level for calculating net ecosystem exchange of carbon, which can complement direct soil measurement. While gains in soil carbon are important, these gains are slow and difficult to quantify because of the very high spatial variability in soil carbon and because of the difficulty and expense of soil sampling. Furthermore, gains in soil carbon can be easily reversed by changes in practices, weather conditions, or other factors. These challenges mean that meaningful measurement of soil carbon gains and losses require strong protocols and a robust, long-term sampling (with periodic re-sampling) and analysis strategy.

There have been national programmatic frameworks in the past where soil carbon has been measured at designated locations, such as the Natural Resources Inventory (NRI) Soil Carbon Monitoring Network and the Rapid Carbon Assessment (RaCA), but there is currently no ability to systematically monitor soil carbon over time for agricultural systems. As a result, there are gaps in our understanding of the impact of agricultural practices on changes in soil carbon. Furthermore, significant uncertainties and biases exist in current soil carbon models. A key challenge to reducing these uncertainties has been the lack of data that can be used to calibrate these models effectively. Increased monitoring and research to assess the impacts of agricultural management on soil carbon change over time can provide data needed to reduce uncertainties and improve accuracy of soil carbon models; accelerate adoption of the most effective practices; support the Administration's policy goals; and inform and improve the U.S. GHG Inventory.

Supporting Task: USDA will establish an agricultural soil carbon monitoring network to collect the data necessary for improving model estimates.

USDA will establish a national Soil Organic Carbon Monitoring and Research Network (SOC monitoring network) to monitor soil carbon changes over time across the agriculture landscape and develop a network of on-site experiments on carbon sequestration from targeted management practices. The SOC monitoring network will take advantage of existing SOC datasets (e.g., USDA's Forest Inventory Analysis Program [FIA]), existing federal research sites (e.g., Long-Term Agricultural Research sites and Conservation Effects Assessment Program sites), university experimental farms, and other soil carbon monitoring networks. Soil samples will be shipped to certified laboratories that measure bulk density and soil carbon by dry combustion.

As part of this effort, USDA will prepare and publish standardized, georeferenced, incremental protocols for soil testing and sampling methods. USDA will apply these methods across a network of several thousand monitoring sites[dd] to create a database of soil carbon measurements and ensure that the data collected will be made available to internal and external stakeholders to the greatest extent possible, subject to existing privacy and confidentiality codes and statutes. In turn, these data can be used to improve calibration and validation of models used to estimate soil carbon changes (e.g., DayCent), improve characterization of the soil carbon impacts of agricultural management practices, and document the sources and magnitude of uncertainty in our carbon stock estimates. USDA will implement these model improvement efforts in close collaboration with the wider modeling community, leveraging established collaborative processes including Model Intercomparison Projects (MIPs) and ensemble modeling. Having more accurate models will support conservation programming decisions, provide better outcome estimates from conservation programs, and improve the U.S. GHG Inventory soil carbon estimates.

Supporting Task: Accelerate development of low-cost solutions for soil carbon measurement.

Soil carbon measurement technologies range from traditional soil core sampling (e.g., dry combustion) to remote sensing techniques (e.g., integration of machine learning and unmanned aircraft systems with hyperspectral capabilities), to more recent *in situ* technologies that can quickly assess soil carbon without the need to take soil samples (e.g., proximal soil sensing).

[dd] Selected sites have been sampled at least once, meaning there is a baseline of soil carbon stock. Frequency of re-sampling will be approximately five years because soil carbon changes slowly.

Given the increased need for soil carbon measurements to improve GHG MMRV, it is imperative to identify accurate, low-cost solutions (e.g., spectroscopy) that can meet agency objectives. USDA, through ARS, and DOE, through its Advanced Research Projects Agency-Energy (ARPA-E) program, are investing in technologies to measure and monitor soil carbon. USDA and DOE will develop criteria to evaluate these technologies (e.g., accuracy, scalability, etc.), with the aim of adopting the best technology or technologies for deployment in the SOC monitoring network and to potentially address other soil carbon monitoring goals across the USG.

Use Atmospheric-Based Approaches to Augment or Verify Agricultural Data

Implementing agencies include: USDA, NASA, NOAA

Remote sensing data that provides information on agricultural characteristics, such as above-ground biomass, cover crop, and tillage, have the potential to lower costs, improve quality, reduce uncertainty, and reduce time lags in generating GHG emissions information, as well as verification of model outputs. Increased use of remote sensing can benefit multiple agriculture applications, including improving the temporal and spatial resolution of land cover and land use change analysis, increase accuracy of tracking agricultural and land management practices, generate additional biophysical data, and improve model parameterization. Many of these capabilities (e.g., soil/litter/detritus mapping or remote sensing of methane from livestock operations) are still at lower levels of application/operations and technology readiness. Similarly, atmospheric measurements from federal and commercial observing systems can potentially provide verification and validation for activity-based GHG estimates in the agriculture sector.

Supporting Task: Use tall tower measurements to verify and improve models and inventories.

There is a critical need to better estimate agricultural emissions and to understand the impacts of wide-scale adoption of climate smart agricultural practices on entity, regional, and national emissions. Efforts to scale up to regional and national emissions estimates have generally relied on activity-based approaches. Verification of these estimates with atmospheric-based approaches would accelerate improvements to models and inventories, including identifying missing or underrepresented GHG emissions sources.

USDA (ARS), in collaboration with NOAA and university collaborators, will explore the use of tall tower (300 foot) measurements to verify and improve models and inventories, and to identify previously unknown emissions hot spots and episodes. Tall tower measurements consist of continuous high-precision concentration measurements of air drawn from the top of an FM radio tower, or similar tower. Current tall tower data show that regional inventories and models substantially underestimate mid-continent (Corn Belt) emissions of nitrous oxide. There are at least two possible reasons; one is that inventories are simply missing key contributing land-use classifications. Another is that they are not adequately modeling some of the key processes. Emissions estimates subject to either source of error can be adjusted through inverse methods, in which tall tower data are used recursively in conjunction with a priori emissions estimates and atmospheric transport models to modify the original inventory or model estimates until they best reproduce the concentration measurements made at the tower.

Supporting Task: Explore opportunities to use remote sensing to enhance or augment data collected by other methods.

NASA and USDA are finalizing a memorandum of understanding on collaboration to support climate-smart agriculture, which includes exploring opportunities to leverage remote sensing data to enhance or augment current sources of agricultural data. Remote sensing is an effective way to gather information on some agricultural practices (till/no till, cover crops, etc.). This approach can be more efficient, more comprehensive, more reliable, and less expensive than surveying farms. USDA will explore increased use of remote sensing to gather data on agricultural practices, in conjunction with the goal of improving understanding of how those practices affect carbon flows, other environmental variables, and yields. Additionally, methane data from federal and non-federal observing systems can potentially provide independent confirmation for bottom-up methane estimates in agriculture, as well as identify and quantify emissions sources and patterns that can help producers identify opportunities for efficiencies and mitigation that could save money in the long run.

Agricultural GHG Data Management

Implementing agencies include: USDA

Interoperability and sharing of data are critical to obtaining value from the GHGMMIS. Sharing and accessing data across multiple agencies will advance abilities to develop, test, implement, and visualize new data sources, models, technologies, and remote-sensing capabilities. However, agencies often lack the ability to easily share data, particularly data that include personally identifiable information. In addition, it is essential to share data with the broader research and policy communities to improve understanding of GHG emissions from agriculture and to track and accelerate progress in managing those emissions.

The proper balance between data access for scientific and programmatic analyses and data privacy is a critical design focus of USDA's data management activities. GHG data should be open and transparent to the extent permitted by privacy laws, and giving researchers access to information on GHG emissions and associated data on agricultural practices, yields, soil types, etc., will enable advances in understanding of how to control emissions while optimizing agricultural outcomes. With these considerations in mind, USDA plans to improve the availability and transparency of its GHG-related scientific data (consistent with statutory restrictions) for the public. USDA proposes to engage external stakeholders and data experts, and other agencies, for input and collaborative data design work to enhance interoperability and accessibility of data to support improved GHG estimates for conservation programs and inventories. USDA also works through existing policies (e.g., OMB-13-13, Geospatial Data Act of 2018 and associated Departmental Regulations) to support FAIRER data principles.[ee]

Several data management practices need to be supported as new data sources come online and as existing data sources are integrated. These practices include developing and implementing data standards (e.g., setting a minimum bar of quality for compiled data), determining data schemas (e.g., developing definitions and units for data collection), recording data lineage (e.g.,

[ee] The FAIRER principles are described in Objective 4: Improve Latency, Completeness, and Accessibility of GHG Data in the National Objectives for Advancing the U.S. GHGMMIS section.

documenting where data come from), documenting metadata (e.g., describing key information about the data), performing quality control (e.g., confirming data were not mis-entered), and addressing security (e.g., protecting data from alteration), while at the same time abiding by statutory requirements and producer privacy concerns. Advancing data management at this scale requires significant effort, but establishing strong data management practices and standards is expected to increase the interoperability, accessibility, and value of future data for decision-making.

Supporting Task: Advance data management, infrastructure, and capacity for field data necessary for improving agricultural model estimates.

Large datasets that span locations and use compatible methods are extremely valuable for advancing research and modeling. Funding from the IRA provides an opportunity to align agricultural data with best practices and data management principles to accelerate research that leads to model improvements and adoption of GHG-reducing strategies.

USDA is proposing advancing data management infrastructure and capacity for field and remote sensing data necessary for improving model estimates on mitigation benefits and GHG emissions. The proposed work builds on other efforts (e.g., the SOC monitoring network) with the necessary IT-related infrastructure to enable the combination and analysis of previously siloed data and support interoperability of new data. The FAIRER principles apply to the work to enable “apples to apples” statistical models and improve the quality and usability of the data across multiple platforms. The proposed work includes detailed data design work, alignment of data schemas and conventions, and use of international standards where appropriate. A blueprint of the data standards and conventions will be developed that will be published for public use, allowing immediate use and testing through a continuous improvement feedback process. The proposed data design work also supports other efforts with data design and architecture work to develop required automation, including setting data standards for data collection, processing, QA/QC, security, aggregations, and reporting. Evaluation of privacy requests, codes and statutes, and options for sharing data in an anonymized manner are important components of the data management work. To ensure widespread applicability and facilitate data harmonization for improving models and estimates, the proposed external engagement is significant and will inform the data management infrastructure and capacity work.

Energy

The energy sector is the largest source of carbon dioxide emissions in the United States, representing 96.5% of the Nation’s carbon dioxide emissions in 2021.[36] The sector is also increasingly recognized as a significant source of methane emissions (approximately 40% of national methane emissions in 2021).[37] Energy-related emissions sources include, but are not limited to, fossil fuel combustion, non-energy uses of fossil fuels, incineration of waste, coal mining, abandoned underground coal mines, petroleum systems, natural gas systems, and abandoned oil and gas wells. In addition, the U.S. GHG inventory accounts for international bunker fuels and biomass and biofuel consumption.

Multiple efforts across the USG are focused on estimating emissions from the energy sector, presenting the opportunity to further enhance coordination and integration of existing activities and capabilities.

Oil and Gas Supply Chain

Implementing agencies include: DOE, EPA, NASA, NOAA

Methane emissions from the petroleum and natural gas supply chain, from production to distribution, are one of the largest contributors to U.S. methane emissions.[38] A significant fraction of the emissions from the oil and gas sector originates from a relatively small fraction of high-emitting emissions sources. The relative frequency of these high-emitting emissions sources is difficult to predict, and high-emitting sources vary between production regions.[39] Continued and increased monitoring will provide important opportunities to understand and mitigate emissions from the oil and gas supply chain.

Activity-based (bottom-up) emissions estimates for this source category are typically calculated by multiplying estimated or actual counts of specific devices (e.g., wells, compressors, and pneumatic controllers) and operations (e.g., compressor blowdowns and well completions) by emissions factors that vary depending on the level of control and operational practices possible for the equipment type or operation. Flaring emissions can be estimated from data on production volumes together with information on associated gas disposition (recovered, vented, or flared) and flaring efficiency. These approaches allow for quantification of emissions totals and trends for equipment and practices, which can show changes in emissions due to specific activities or changes in technology or practices. Emissions from anomalous large events[ff] are quantified through other methods.

Atmospheric-based (top-down) measurement and monitoring capabilities for detecting and quantifying methane emissions, including pinpointing point source emissions at individual facilities, are improving, with various remote sensing technologies reaching maturity. Although these detection methods are identifying emissions sources, their ability to quantify these emissions with high certainty can be improved. Advances in calibration methodologies and emissions quantification approaches that account for local atmospheric conditions are needed to advance these remote sensing capabilities.

Airborne methane surveys conducted in the past five years in multiple states have been used to identify super-emitters, in some cases leading to voluntary leak repair efforts, but largely have been limited to short-term demonstrations as part of the current methane research enterprise. Additionally, NOAA researchers have used airborne surveys to conduct multiple studies on variable methane leak rates and other chemicals emitted during natural gas production. These studies are intended to help industry identify conditions and techniques that minimize leaks during gas production as well as provide atmospheric measurements for comparison to emissions inventories. Spaceborne measurements of methane super-emitters from NASA's EMIT (Earth Surface Mineral Dust Source Investigation) instrument on the International Space Station have

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[ff] Anomalous leak events include emergency pressure relieving equipment and well blowouts. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories specifies that these events should be evaluated and estimated on a case-by-case basis using the best-available data.

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also led to voluntary leak repair efforts. In addition to identifying super-emitters, these methods provide estimates of methane emissions totals, at least from large sources, at varying spatial scales. As quantification capabilities are improved, these can then better attribute emissions from the oil and gas sector in the areas surveyed.

Advancing measurement and monitoring capabilities for the oil and gas sector and improved collaboration between activity-based and atmospheric-based data collection efforts could potentially strengthen the use of empirical data to validate activity-based emissions data, thus forming a more complete understanding of methane emissions sources and changes over time. Furthermore, enhanced information may inform policy decisions and identify opportunities for action that otherwise may not have been apparent or acted upon in a timely fashion. Many of the same measurement methods used are applicable to other high-priority areas (e.g., coal mines, landfills, and wetlands).

Recent proposed federal regulatory action associated with the IRA[gg] would enhance the use of empirical methane emissions data to meet regulatory reporting requirements. Several other recent proposed or final actions at the federal level, such as those developed by the Bureau of Land Management or the Pipeline and Hazardous Materials Safety Administration, will also impact emissions of methane from the oil and gas supply chain. The supporting tasks outlined below are expected to be complementary to these ongoing activities.

Supporting Task: Establish the Permian Basin as a testbed for improving measurement and modeling of methane emissions.

The Permian Basin is the largest, most productive oil and gas production basin in the U.S. and one of the most well-studied methane-emitting regions in the country. The Permian Basin encompasses an area that is approximately 250 miles wide and 300 miles long, with more than 7,000 producing fields. Along with the vast amounts of oil that are produced, the Permian also produces a large amount of associated natural gas. As of 2022, the Permian Basin is responsible for 43% of the Nation's oil production and 17% of the Nation's natural gas production.[40] The Permian Basin is also home to a large number of historic oil and natural gas operations, with nearly half a million vertical wells completed since the 1930s.[41]

Existing GHG measurement and monitoring efforts in the Permian Basin, either in progress[hh] or planned, hold good promise for the Basin's use as a measurement testbed due to the vast amounts of oil and natural gas produced. This large area, with its varying topography, number of producing fields, and large percentage of nationwide production, enables technologies to be

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[gg] The IRA established a waste emissions charge for methane from applicable oil and gas facilities that report more than 25,000 metric tons carbon dioxide equivalent (CO_2e) per year to GHGRP Subpart W and that exceed statutorily specified waste emissions thresholds. The IRA directed EPA to revise GHGRP subpart W to ensure reporting and calculation of charges are based on empirical data, accurately reflect total methane emissions, and allow operators to submit appropriate empirical data to demonstrate the extent to which a charge is owed.

[hh] Current efforts include the installation of a network of methane sensors on several mountain-top sites and communication towers encircling the Delaware portion of the Permian Basin, airborne remote sensing and direct sampling efforts, and an ARPA-E surface-based remote sensing effort anticipated to operate at the facility component level.

tested over a wide array of conditions. Additionally, the Permian Basin spans two states, Texas and New Mexico, allowing for considerations surrounding differing regulatory environments for technologies to be tested and validated against specific regulatory frameworks. All of these aspects make the Permian Basin an ideal testbed for methane emissions quantification technologies. DOE is utilizing a variety of funding mechanisms (including grants and cooperative agreements) to advance basin-specific assessments related to the quantification and characterization of methane emissions. These assessments are intended to accelerate the availability of emissions data to support policymakers and technology developers in the advancement of transformational concepts enabling a "leak tight" natural gas value chain.

DOE and stakeholders from academia and industry plan to advance, integrate, and field-test surface-based methane quantification networks for the characterization of emissions across wide areas of interest in the Permian Basin. Field assessments of methane emissions quantification technologies in a basin-specific approach will enable researchers and assessors to better understand methane emissions across the natural gas supply chain and provide more accurate information to inform the development of emissions factors used by emissions inventories for activity-based (bottom-up) analysis. DOE, in consultation with other federal agencies, also plans to develop an approach for the creation of an integrated methane monitoring platform to reconcile top-down and bottom-up emissions inventory measurement methods by leveraging the expertise of academia, industry, and technology developers through competitive solicitation and intramural R&D supported efforts.

More systematic, routine measurements of methane emissions in this basin would represent a significant improvement over past efforts, which have been limited to small field campaigns and short-term demonstrations. Additionally, coordinating upcoming measurement campaigns to simultaneously collect activity and atmospheric data and establishing long-term monitoring efforts in select areas would contribute to enhanced understanding of processes[ii] and trends in emissions over time, improved characterization of super-emitters, and provide higher resolution data that can be useful to validate satellite-based remote sensing techniques.

Where possible, collection of measurement data that enhances key emissions and activity data on production equipment (e.g., tanks, valves, and similar components) would bring significant improvements to information used to develop and assess regulatory and voluntary actions. This would also contribute to producing spatially explicit emissions data to significantly improve atmospheric methods, providing a basis for continuous monitoring at basin or sub-basin levels using surface networks similar to those used in urban areas. Five of the multi-year research projects awarded through DOE's Innovative Methane Measurement, Monitoring, and Mitigation Technologies (iM4 Technologies) funding opportunity announcement are seeking to improve emissions inventory estimates by gathering and analyzing data from specific on-site equipment associated with resource production (with a particular focus on storage tanks), as well as multi-

[ii] Atmospheric monitoring provides whole-basin emissions quantification that can be used to test the process-based understanding about emissions that is encapsulated in emissions modeling systems. Comparative analysis of methane emissions estimates from activity- and atmospheric-based approaches will help improve understanding of the methane emissions of oil and gas production.

scale, basin-specific atmospheric monitoring field projects across natural gas-producing areas of the United States.

Supporting Task: Address technical gaps associated with surface-based[jj] methane monitoring through demonstration projects.

DOE has awarded two multi-year projects through DOE's iM4 Technologies funding opportunity announcement that are demonstrating continuous surface-based methane monitoring networks in several producing basins across the United States and are designed to address a wide range of gaps, including the following:

- Accurately detecting methane emissions sources, from fugitive emissions from leaking connections to periodic venting episodes to incomplete combustion (e.g., flares and engine slip).
- Accurately quantifying methane emissions rates, from relatively small volumes to higher volume super-emitters.
- Studying variations in emissions due to environmental factors, including temperature variation, changing weather conditions, changes in ambient air quality, wind direction and velocity, and other parameters that could affect continuous monitoring.
- Considering geographical characteristics for monitoring network design and communications optimization, including topography that could affect line of sight communications and impact effective methane monitoring for scalable demonstration.

The anticipated results from these projects, valued at nearly $47 million in federal funding over four years, will accelerate the deployment of methane quantification technology and contribute to better understanding of monitoring parameters such as detection sensitivity (concentration) and emissions rate sensitivity (e.g., kg/hour).[42]

Supporting Task: Enhance capabilities for testing the precision and accuracy of advanced measurement technologies.

Among other sources, approximately 211 million metric tons of methane are emitted across the oil and natural gas value chain[43], which consists of more than two million miles of pipelines; more than four million actively producing, abandoned, or repurposed oil and natural gas wells; and more than 10,000-unit operations consisting of natural gas processing plants, compressor stations, and gathering stations. A leading challenge associated with mitigating methane emissions from the oil and natural gas value chain is the complexity of these systems, considering the magnitude of the number of individual operating components widely distributed across the country.

There has been significant progress made on surface-based point-source technologies and methodologies for detecting and quantifying methane emissions. These include static monitors,

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[jj] "Surface-based monitoring," in the context of DOE's iM4 Technologies program, refers to fixed location sensing elements utilized as a scalable network capable of integrating and disseminating emissions data in near real-time to better characterize fugitive emissions associated with hydrocarbon resource production.

hand-held sensing and measurement devices, and vehicle-based detection sensors. However, many of these surface-based technologies are limited in their ability to quickly assess large areas, require significant "human-in-the-loop" operation and data interpretation, and have high operational costs, thereby limiting their ability to cost effectively scale up to the regional scale. There is a need for continuous, surface-based gridded monitoring of methane emissions that can quickly detect and identify intermittent super-emitters so that they can be effectively mitigated as soon as possible. Additionally, regionally integrated platforms for methane emissions monitoring would ideally include atmospheric technologies that can be coupled with the surface-based technologies mentioned above. These could include stationary survey approaches, manned and unmanned aerial surveys, and satellite surveys.

First developed under the ARPA-E MONITOR program in 2016, the Methane Emissions Technology Evaluation Center (METEC) was originally designed to support the testing of next-generation leak detection and quantification methods by providing the infrastructure and conditions that emulate the emissions behavior of operational upstream and midstream oil and gas facilities. DOE continues to support METEC through the Office of Fossil Energy and Carbon Management and, in 2023, will invest in METEC's efforts to modernize and expand existing testing capabilities. Specifically, testing capabilities will be extended to include representations of onshore midstream gas processing facilities and complex offshore facilities with their associated unique air turbulence and sunlight reflection characteristics. Offshore methane emissions are difficult to monitor from space due to current limitation in sensing technology. The high absorption of short-wave infrared (SWIR) radiation by water limits the amount of reflected light reaching the satellite sensor and, subsequently, limits the capability of current sensors to separate the absorption of methane in the SWIR from instrument noise and sea surface roughness.[44]

Work will also focus on the development of repeatable protocols for testing leak detection and quantification solutions, coordination of national and international efforts to standardize such protocols, and continued controlled testing of industry-generated solutions. The field-based validation of technologies, tools, and processes for methane emissions detection and quantification will accelerate the adoption of advanced monitoring systems for basin-wide emissions across both the United States and internationally. DOE also will support METEC efforts to acquire large, realistic data sets needed as training data for machine learning, as test data for improved dispersion modeling, and as test data for computational fluid dynamics and large eddy simulation models. This type and volume of data collection will enable the models and the machine learning algorithms to improve accuracy and precision, as they reflect a realistic operational system, from a site-specific to basin-scale assessment. Lastly, DOE is exploring opportunities to test and validate satellite technologies via "scaled" and "scheduled" controlled releases of methane from the METEC facility to better characterize remote sensing platforms as a viable means for methane emissions monitoring.

DOE is looking to expand the regional footprint of field-testing sites like METEC to other basins and places across the United States. Adding region-specific testing facilities will help to better quantify and improve emissions monitoring approaches to account for infrastructure maturity, changing environmental conditions, and unique geographical constraints, as well as basin-specific production, transport, and storage considerations.

Supporting Task: Develop a process for systematic identification and quantification of large, anomalous oil and gas emissions events for inclusion in the national GHG inventory.

Anomalous, large emissions events can occur across methane sources and can have highly variable emissions. Examples of such events include production and storage well blowouts in the petroleum and natural gas systems source categories. These are events that are not captured using available emissions factors.

In recent years, EPA began incorporating information on large leak events into the U.S. GHG Inventory. EPA first incorporated a large leak event into the 2017 U.S. GHG Inventory with the inclusion of an emissions estimate from the Aliso Canyon storage well event.[45] In 2022, EPA incorporated estimates for three additional large leak events into the U.S. GHG Inventory.[46]

EPA is working with NASA through the U.S. GHG Center on incorporating additional leak events into the U.S. GHG Inventory time series. The leak events of interest include those occurring beginning in 1990 (first year of U.S. GHG Inventory time series) and extending into the future. It is likely that a variety of data sources (e.g., current and upcoming satellites, historical records, flight campaigns) will be used to quantify these emissions for incorporation into the U.S. GHG Inventory and that events captured will eventually include other methane sources in addition to those from petroleum and natural gas systems. This work will help improve completeness of the U.S. GHG Inventory estimates and improve understanding of magnitude and frequency of large emissions events.

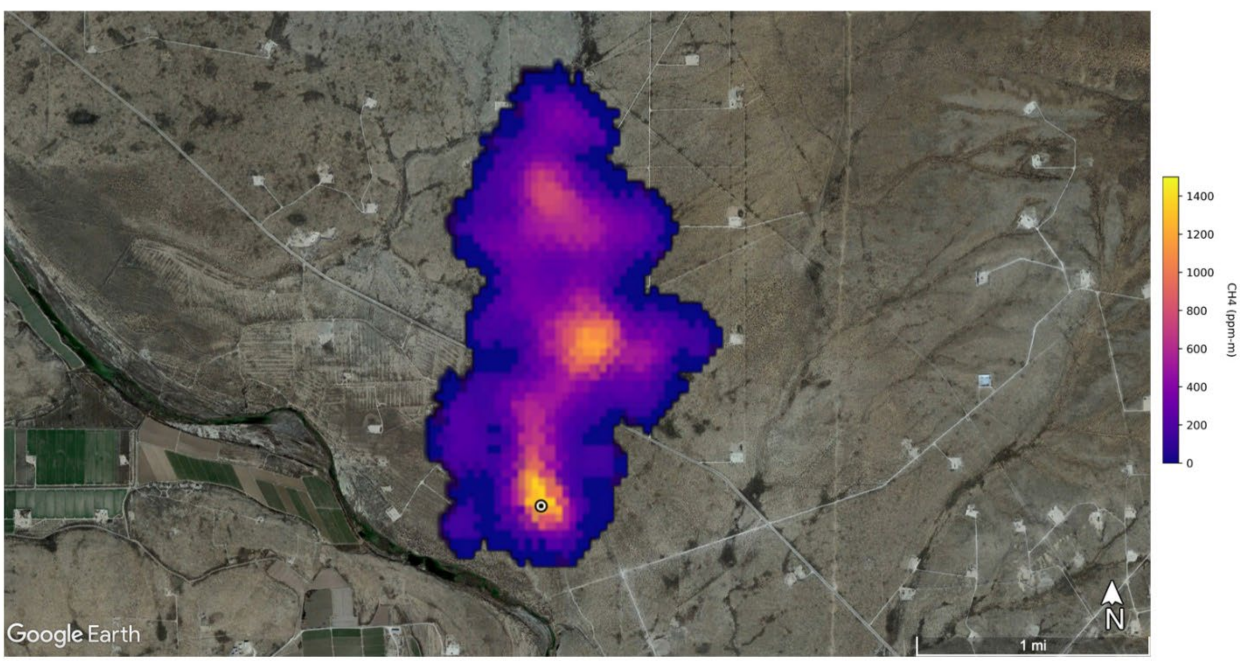

Figure 7. *A plume of methane is detected flowing from an area southeast of Carlsbad, New Mexico, in an image that uses data from NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission. (Image credit: NASA Jet Propulsion Laboratory)*

Coal Mines

Implementing agencies include: DOI-USGS, DOI-Bureau of Land Management (BLM), DOI-Office of Surface Mining Reclamation and Enforcement (OSMRE), NIST, NASA, NOAA, EPA, and DOE.

Active and abandoned[kk] surface and underground coal mines are significant methane emitters and modest contributors to carbon dioxide emissions.[47] In 2021, methane emissions from coal mining and abandoned coal mines accounted for about 7% of total U.S. methane emissions and about 1% of total U.S. GHG emissions (based on million metric tons of carbon dioxide equivalent).[48] Coal mining is expected to account for approximately 10% of global methane emissions by 2030.[49] The majority of methane emissions (66%) from coal mines come from degasification and ventilation systems in active underground coal mines.[50] Surface mines contribute roughly 13% of total emissions from coal mines, post-mining activities at underground and surface mines contribute 11%, and abandoned mines contribute 9%.[51]

To estimate annual emissions from coal mining activities, the IPCC recommends a range of methods. For one approach, national GHG inventories rely on IPCC default emissions factors or use national- or basin-specific emissions factors.[52] Alternatively, in combination with coal production data, more accurate estimates can be based on site-specific measurements at active underground coal mines, which are generally available in the United States due to regulatory safety requirements.[53] Remote sensing methods, such as satellite and aerial technologies, have not yet been used to quantify emissions from coal mining activities for GHG inventory purposes, but recent advances have been made, enabling the use of these technologies to help verify ground-based measurements and estimates.[54] However, more work is needed to reconcile top-down and bottom-up emissions estimates. Because of current GHG reporting requirements[55] and public awareness of GHG emissions and their contribution to climate change, coal mine operators are becoming more interested in reducing methane emissions and are willing to participate in emissions measurement programs. Abandoned coal mines will be a second priority for emissions studies because of their lower emissions compared to active mines. Coal mine methane emissions reduction strategies will benefit from the application of multiple measurement approaches. Targeted enhancements in emissions data will advance the capability to gauge the impact of efforts to reduce emissions from active or abandoned mines.

Supporting Task: Form a Coal Mine Emissions Working Group that will coordinate federal efforts to improve methane emissions estimates from coal mines.

Significant expertise and capabilities exist within the USG to conduct enhanced measurement of methane emissions, which could be better leveraged to improve understanding and estimation of methane emissions from coal mines. In 2024, USGS, BLM, OSMRE, EPA, DOE, NIST, NOAA,

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[kk] The Office of Surface Mining Reclamation and Enforcement uses the following definition for abandoned coal mines, which is based on Title IV of the Surface Mining Control and Reclamation Act of 1977 (SMCRA): In general, to be eligible for reclamation under Title IV of SMCRA, the site must have been "mined for coal or . . . affected by such mining, waste banks, coal processing, or other coal mining processes . . . and abandoned or left in an inadequate reclamation status prior to August 3, 1977, and for which there is no continuing reclamation responsibility under State or other Federal laws." 30 U.S.C. 1234.

and NASA will establish a working group to enhance coordination of future demonstrations and research related to coal mine emissions. The working group will consist of a mix of agencies that possess expertise in sensor technologies, support methane monitoring networks, and generate mine emissions data and research. In the near term, agencies will focus on improving methane emissions estimates from gassy[ll] underground active coal mines, which are the primary contributors of methane emissions from all coal mine types (surface, underground, and abandoned).

Supporting Task: Reconcile methane emissions estimates from atmospheric-based approaches with activity-based approaches at active underground coal mines.

GHG emissions estimates for active underground coal mines in the United States are largely derived from annual GHGRP data reported to the EPA and estimated based on episodic measurement data from mining activities at individual mines. To date, there has not been a coordinated effort to combine and reconcile bottom-up and top-down measurements to quantify and validate reported emissions from coal mines over time.

DOI will lead agencies in the Coal Mine Emissions Working Group in implementing a demonstration project that generates data from atmospheric-based approaches and reconciles this information with data from activity-based approaches. The goal of the demonstration project is to address the shortcomings of both approaches and narrow the uncertainty of coal mine emissions by incorporation of top-down feedback with estimates derived from periodic ventilation air measurements.

Active underground coal mines produce the majority of GHG emissions from the coal mining sector and will be the primary focus of the working group. Better GHG emissions measurements from active underground coal mines may help mine operators mitigate emissions and potentially help lower emissions after mine closures.

The agencies have identified an active coal mine in southwestern Virginia for the demonstration project, which will consist of installing instrumentation to estimate continuous emissions from active ventilation shafts and ambient near-surface methane concentrations. DOE, NIST and USGS will provide expertise related to surface monitoring design and instrumentation. NASA, NOAA, and potentially other entities will provide simultaneous satellite and/or airborne monitoring and assist with data integration and reconciliation. EPA will assist with access to reported mine emissions data. The demonstration project is expected to last two years and may be expanded to other underground mine locations. Expected results include first-of-a-kind reconciled simultaneous bottom-up and top-down emissions estimates from active underground coal mines. Results published at the end of the demonstration are expected to include lessons learned for future coal mine measurement studies and support coal mine methane abatement strategies.

[ll] Gassy active underground coal mines emit more than 100,000 cubic feet (7,901 metric tons) of methane per day.

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Waste

The Waste Sector consists of Municipal Solid Waste (MSW) landfills, industrial waste landfills, industrial and municipal wastewater treatment systems, and facilities that operate combustors or incinerators for the disposal of nonhazardous solid waste.[56] MSW landfills are the largest source of methane emissions in the Waste Sector and are the third-largest source of anthropogenic methane emissions in the United States.[57]

Municipal Solid Waste Landfills

Implementing agencies include: EPA, NIST, NOAA

The MSW subcategory, as outlined in the GHGRP, consists of emissions from landfills, landfill gas collection systems, and destruction devices for landfill gases.[mm] This subcategory is a high priority for increased monitoring because recent airborne methane surveys suggest that emissions may be higher and more persistent than previously expected.[58,59] Emissions of landfill gas to the air are determined in part by the design and operation of the gas collection and control system and the operational characteristics of the site. Factors such as flooded collection wells, cover integrity issues, planned maintenance activities, and equipment failures can result in elevated emissions compared to reported GHGRP estimates and can persist for extended periods of time. In many cases, the presence of preventable excess emissions that may require action cannot be known without some form of methane emissions measurement. Walking survey surface emissions measurements (SEM) required quarterly by Clean Air Act regulations are not able to detect all anomalous emissions at a landfill that occur over a large footprint, some extending for hundreds of acres.

Current landfill emissions estimates typically come from activity based process models. Improving the data upon which these are based and validated across a broad population of landfill sites will enhance the performance of landfill models. Emissions factors are often based on episodic observational campaigns lasting from a few days to several weeks and may not properly characterize the range of changes in emissions due to varying conditions (including barometric pressure and extreme precipitation events). The GHGRP currently uses two different emissions calculation approaches that show significant differences in observed emissions due in large part to uncertainties in landfill gas collection efficacy, which can be informed by measurements.

Research efforts have demonstrated that observing approaches utilizing a combination of aircraft and satellite measurements and near-continuous, surface-based observations of these landfills have the potential to advance understanding of emissions from this subsector, improve MSW landfill emissions modeling, and identify and better quantify super-emitting sites. Increased availability of accurate data supporting modeling will reduce estimation uncertainty and support actions that result in near-term reductions of methane. Enhanced understanding of landfills emissions over time and over varying environmental conditions can inform development of cost-effective management strategies.

[mm] Destruction devices for landfill gases include boilers, engines, and flares.

Supporting Task: Establish measurement test beds that combine atmospheric observations of carbon dioxide and methane with activity data from landfill operations to improve Municipal Solid Waste landfill emissions models, emissions factors, and activity data.

NIST, in coordination with EPA, NASA, and NOAA, will support a landfill measurement test bed initiative as part of the larger NIST Northeast Corridor Urban Test Bed project, which quantifies GHG fluxes in the Washington, DC, and Baltimore, MD, urban regions. The agencies envision the test bed initiative as a multi-year, multi-landfill investigation of emissions that utilizes current EPA-recognized emissions measurement methods, for example SEM walking surveys, and adds to these surface-based methods and selected top-down approaches to determine the carbon dioxide and methane concentration fields across the landfill's extent. NIST has recently acquired the use of an airborne hyperspectral imaging spectrometer that has potential to map the emissions plume exiting the landfill at high spatial resolution. These datasets, combined with metrological data and models, will improve characterization of MSW landfill emissions. Simultaneously obtained activity data from the landfill operator will provide the means to relate the emissions factor data derived from atmospheric measurements with the activity data needed to improve landfill emissions models. This research is planned to have a duration of several years, aimed at capturing accurate data from diurnal to seasonal scales and to better quantify the impact that changing seasons and temperature have on emissions.

Supporting Task: Advance development of cost-effective measurement and monitoring approaches for landfill emissions.

Agencies are advancing development of cost-effective measurement and monitoring approaches through extramural grants, intramural research, and collaboration with external data providers on validation and testing efforts. EPA's Science to Achieve Results (STAR) Grant program solicitation, "Understanding and Control of Municipal Solid Waste Landfill Air Emissions," is intended to address the need for cost-effective approaches for quantifying landfill methane emissions that utilize stationary, mobile, aerial, and remote sensing technologies. Projects under this solicitation will demonstrate and validate approaches to quantifying emissions from various landfill characteristics (e.g., footprint, topography, cover material) and management conditions under changing environmental conditions and increase the ease of use and evaluation of GHG reduction strategies and technologies. EPA recently announced five awards, totaling $4.6 million, for the STAR solicitation.[60]

Partially supported through funding from the IRA, EPA's emerging intramural landfill research program will complement EPA STAR efforts through targeted development of selected landfill monitoring methods that can be routinely employed by landfill site operators to improve understanding of emissions and operational impacts. EPA's program will also collaborate with NIST, NASA, and other government agencies to evaluate optimal multi-tiered measurement approaches.

Together, remote sensing and continuous measurements are likely more effective landfill monitoring solutions, compared to infrequently executed SEM walking surveys that cannot determine whole-facility emissions and avoid areas of the landfill like the active disposal area. To facilitate use of remote sensing data as a more cost-effective tool for near-term identification of "super emitter" landfills, agencies will support efforts that provide independent validation of third-party measurements by sharing expertise on scientifically based methods and instrumenting landfill test bed(s) to support validation. In limited cases, agencies may directly fund airborne validation campaigns and evaluations of commercial satellite data. EPA is currently participating with NASA's Commercial Small Sat Data Acquisition program to evaluate commercial data to detect and quantify landfill methane emissions.

Natural Systems Emissions and Removals

The U.S. GHGMMIS will support the measurement and monitoring of GHG emissions and removals from natural systems—including both the processes that occur naturally within the biosphere, as well as emissions and removals from natural systems that occur indirectly or directly because of human activity. For purposes of this Strategy, "natural systems" are defined as oceanic, terrestrial, and coastal and inland aquatic sources and sinks of GHGs, including both managed and unmanaged lands and waters. The definition recognizes that measurement and monitoring approaches for natural systems do not differ significantly based on whether the system is managed or unmanaged and takes a broader approach to defining natural systems compared to the IPCC.[nn]

Globally, oceanic, terrestrial, and aquatic ecosystems annually remove an amount of carbon dioxide equivalent to ~50% of annual anthropogenic emissions.[61] Feedbacks in the biosphere's response to a changing climate (e.g., increased emissions of carbon dioxide and methane from thawing permafrost or reduced oceanic removal of carbon dioxide as a response to climate warming) are believed to reduce this fraction, thereby accelerating global warming.[62] Collectively, land use and management decisions, coupled with natural disturbances, have impacts on natural systems affecting GHG emissions and removals from ecosystems (e.g., reforestation as a forest management practice or converting wetlands for development). Enhancing understanding and quantification of emissions and removals from natural systems will enable the Nation to better gauge the continued effectiveness of natural systems as sinks, track potential climate feedback loops, and isolate natural systems fluxes from fossil fuel or other industrial emissions. Natural systems GHG fluxes will also be important to understand as these sources and sinks make up a much larger share of national emissions and removals as we decarbonize the power and transportation sector.

Robust quantification of GHG emissions and removals ultimately requires systematic observations of the natural biosphere and its full complexity of natural cycles and interactions, and curation of these data for synthesis, modeling, and planning. Enhancing measurement, monitoring, and modeling capabilities would help reduce uncertainties in GHG estimates from

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[nn] The definition adopted here is different from that developed by the IPCC for the purposes of national greenhouse gas inventory reporting to the UNFCCC, and for tracking of progress towards Nationally Determined Contributions under the Paris Agreement. Per the 2006 IPCC guidance and its 2019 Refinement, "Anthropogenic emissions and removals means that greenhouse gas emissions and removals included in national inventories are a result of human activities." The IPCC guidance specifies that for the agriculture, forestry, and other land use (AFOLU) sector, emissions and removals on managed land are taken as a proxy for anthropogenic emissions and removals (IPCC, 2006 and 2019). The GHGMMIS uses a different definition given its broader scope and purpose. For example, emissions and removals occurring on areas considered *unmanaged* and excluded from UNFCCC reporting, are covered by the GHGMMIS.

natural systems, which are currently not as well characterized as some other sectors. This includes geographic regions that are currently data-sparse (and expected to experience significant changes from heatwaves, sea-level rise, flooding, and hurricanes), ecosystems that are potentially large sources and sinks of GHG emissions and removals (including inland wetlands such as peatlands; coastal wetlands such as marshes, seagrasses, mangroves, aquatic systems; and permafrost), and ecosystem and carbon cycle processes that regulate carbon uptake (including ocean carbon uptake models or biogenic uptake and respiration models that elucidate controls of carbon dynamics). Establishing baseline measurements in natural systems would also provide a foundation to compare changes in emissions and removals from a compendium of management, land use, and natural disturbance factors.

Monitoring Ocean Carbon Uptake

The ocean is an important carbon sink that has substantially moderated the pace of global warming by absorbing an amount of carbon dioxide (CO_2) equivalent to more than 25 percent of human emissions.[63] However, the efficiency of oceanic uptake of CO_2 from the atmosphere is expected to decrease as climate change progresses,[64] which would increase the warming effect of CO_2 emissions.

Active monitoring of ocean carbon enables enhanced ability to detect changes in ocean uptake of CO_2 and is being conducted through a global network of instruments (including on cargo ships, ferries, cruise ships, drifting surface platforms, research vessels, and emerging autonomous technologies such as profiling floats) sponsored by federal agencies and international organizations. These data are provided to and synthesized into the Surface Ocean CO_2 Atlas, which is used for quantification of the ocean carbon sink and is the cornerstone of annual updates to the Global Carbon Budget.[65]

Driven by the need for large-scale atmospheric CO_2 removal in meeting climate goals, there is growing interest in enhancing the natural ocean carbon sink through marine CO_2 removal. Effective use of marine CO_2 removal would depend on accurate measurement and verification of intentional CO_2 removals over and above the natural ocean carbon uptake.

Interagency Coordination and Prioritization

Implementing agencies include: DOI, DOE, NASA, NOAA, NSF, USDA, Smithsonian Institution, U.S. Army Corps of Engineers, EPA

Multiple federal agencies contribute important research, modeling capabilities, and monitoring sites dedicated to better understanding fluxes of GHGs from natural systems. These efforts include, but are not limited to the following:

- Understanding the total emissions and removals from specific ecosystems of interest (e.g., wetlands or forests).
- Using *in situ* ground, aircraft- and balloon-based, and remote sensing technologies to validate emissions estimates.

- Using established data assimilation tools (e.g., Carbon Tracker) to incorporate observations to derive regional-scale fluxes associated with natural ecosystems.
- Estimating fluxes from broader global Earth system processes underlying the carbon cycle (including changes in terrestrial, atmospheric, and oceanic carbon fluxes).
- Operating long-term climate change experiments.

The GHGMMIS will build upon existing agency work and coordination on understanding, modeling, and observing GHG fluxes from natural systems, including through the U.S. Global Change Research Program (USGCRP), the Interagency Arctic Research Policy Committee (IARPC), and the EPA-led interagency process to compile GHG data for the U.S. GHG Inventory.

Supporting Task: Develop a prioritized list of ecosystems, impacts, or processes, where targeted measurement efforts would significantly improve GHG estimates.

A variety of natural processes and ecosystems continue to lack well-characterized GHG estimates. This can be for a variety of reasons, including a lack of physical measurement data to better understand processes such as photosynthesis, respiration, disturbance, and methanogenesis; insufficient coverage, timeliness, and frequency of measurements, which hinders the production of policy-relevant analyses; or researchers' focus on scientific questions that are not fully aligned with knowledge gaps that need to be addressed to enhance GHG estimates. The opportunity exists to better coordinate, scale, and streamline measurement and data assimilation efforts to reduce uncertainties of GHG estimates for natural systems.

The development of a prioritized list of ecosystems, impacts, or processes for targeted measurement campaigns would help guide collective federal agency efforts in this area and maximize use of federal resources, as well as inform research topics pursued by the science community. As an initial step to developing this list, agencies would determine a set of criteria to be used to determine high-priority areas for targeted measurement efforts. This could include areas in which existing models or data assimilation tools suggest significant flux uncertainties and are expected to be significant sources of emissions; processes and areas where significant changes in removals are expected due to climate feedbacks and land use change; and areas in which a measurement opportunity exists due to new agency programming or funding. Topics of interest may include building on interior Alaska forest resource estimates,[66] small or prescribed fires versus wildfires, Arctic permafrost, flooded lands, inland waters, wetland GHG fluxes, lateral fluxes of carbon, the fate of carbon in coastal wetlands, or grassland/rangeland ecosystems.

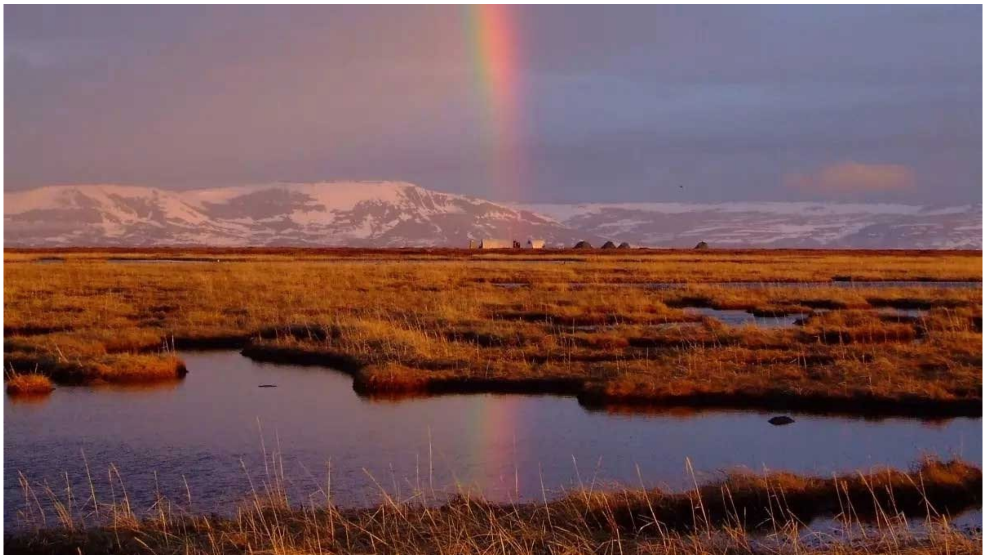

Figure 8. *Scientists are studying how fire and ice drive methane emissions in the Yukon-Kuskokwim Delta, located with the Yukon Delta National Wildlife Refuge in Alaska. (Image credit: U.S. Fish and Wildlife Service)*

Wetlands as a Focus for Targeted Interagency Measurement Efforts

Freshwater wetland and inland aquatic ecosystems are the largest natural source of methane, generating 41%–53% of total global methane emissions,[67] and are a major source of uncertainty in the global methane budget estimate.[68] Enhanced measurement and monitoring of wetlands would help identify hotspots of methane emissions across the Nation and partition these fluxes over space and time (e.g., along landscape and land use gradients or different seasons) to improve emissions factors used to develop GHG inventories and establish baselines that can be used to detect climate-carbon feedbacks. Specific areas that could benefit from targeted interagency efforts include improving understanding of the processes for freshwater and inland water carbon cycling, which would help reconcile inventories and satellite-based measurements of carbon dioxide and methane fluxes; enhancing monitoring of permafrost thaw and the production of thermokarst[oo] wetlands and lakes, which could rapidly increase methane emissions; enhancing monitoring and research of effects of agricultural practices and other land uses on emissions of inland wetlands; and conducting measurement efforts to identify opportunities for pursuing natural climate solutions through management of wetlands.[69]

[oo] Thermokarst is a type of terrain characterized by irregular surfaces of marshy hollows and small hummocks formed as ice-rich permafrost thaws.

Supporting Task: Explore the feasibility of developing a more structured, interagency research program to support ongoing measurement, monitoring, and analysis of methane and carbon dioxide trends and drivers from natural systems.

The USG currently has an inquiry-based research infrastructure primarily based on awarding research grants to individuals or teams at academic institutions. Researchers usually self-organize, propose, and get selected for short-term scientific inquiry-based projects. This structure has led to significant advancements in understanding of natural system GHG emissions and removals, but is not optimal for the proactive, systematic, and sustained monitoring and analysis of natural system GHG fluxes. Specifically, the short-term nature of research investigations makes it difficult to identify and attribute trends in natural system fluxes in a timely fashion and serves as a barrier for tracking long-term trends, or conducting other analytical work that does not fit neatly into the parameters of a short-term research proposal.

A program dedicated to quantifying and analyzing GHG trends and drivers in natural systems could articulate shared, high-priority research or measurement objectives,[pp] reduce the transactional/organizing burden of current short-term, limited research efforts, and lead to more timely identification and attribution of significant changes in GHG fluxes. As part of this research program, agencies will identify existing high-quality monitoring systems, data assimilation frameworks, and databases that are a high priority for continuing and/or enhancing. While many GHG modeling and observing systems were initiated as part of time-limited targeted science investigations, some of these systems may have value beyond the preliminary research goals for which they were designed and could be sustained or transitioned to operational use as appropriate to contribute to longer-term measurement and analysis of GHG flux trends.

Previous synthesis work demonstrates the value of compiling data from PI-led efforts into coordinated analyses and data products.[70,71] Coordinating efforts in this manner ensures that the USG is fully leveraging past investments in research, monitoring, and data management. In exploring options for a more structured research program, agencies would examine potential opportunities to leverage or include existing domestic and international research efforts, including USGCRP, IARPC, the Ocean Policy Committee's Ocean Climate Action Plan (OCAP), the Survey of Reservoir Greenhouse Gas Emissions,[72] USGS's Stream Gage Network, LTER, NEON, Ameriflux, LANDFIRE, NOAA's National Estuarine Research Reserve System, or the Smithsonian Institution's global network of coastal wetland sites.[qq]

Leverage Advancements in Technical Capabilities to Produce Better Natural Systems Data Products

Implementing agencies include: DOI-USGS, NASA, DOE, NOAA, DOD, USDA-Forest Service, NSF, Smithsonian Institution

The technical capabilities for Earth observations and Earth systems modeling have increased significantly. Satellite and airborne remote sensing technologies can shed light on changes in natural systems that provide the foundation for activity-data and emissions estimates, support

[pp] The program could leverage and integrate the prioritized list developed in the previous Supporting Task.

[qq] The Smithsonian Institution also maintains a global database of carbon stocks and fluxes in marshes, mangroves, and seagrasses.

better characterization and attribution of GHG fluxes, provide more granular information that can be integrated into existing monitoring programs, and influence land management practices to optimize sustainability and ecosystem resilience. While remote sensing capabilities can be useful for mapping key terrestrial and aquatic surface features, they require surface-based observations to validate statistical models and sector-specific models that integrate across scales for many key GHG applications.

Supporting Task: Support more robust geospatial data products to improve mapping and classification of natural systems.

The USG produces land use and land cover (LULC) information at the national scale for a wide variety of environmental, land management, and modeling applications based on the Landsat series of satellites. The National Land Cover Database (NLCD), the National Resources Inventory (NRI), and the Forest Inventory and Analysis (FIA) program are the three core databases used in the U.S. GHG Inventory to represent the land use and management base of the United States. The NLCD data are delivered every 2-5 years by USGS, in collaboration with an array of federal agencies. Another LULC product, Land Change Monitoring, Assessment, and Projection (LCMAP), is produced annually, offering a suite of 10 land change and cover products going back to 1985.

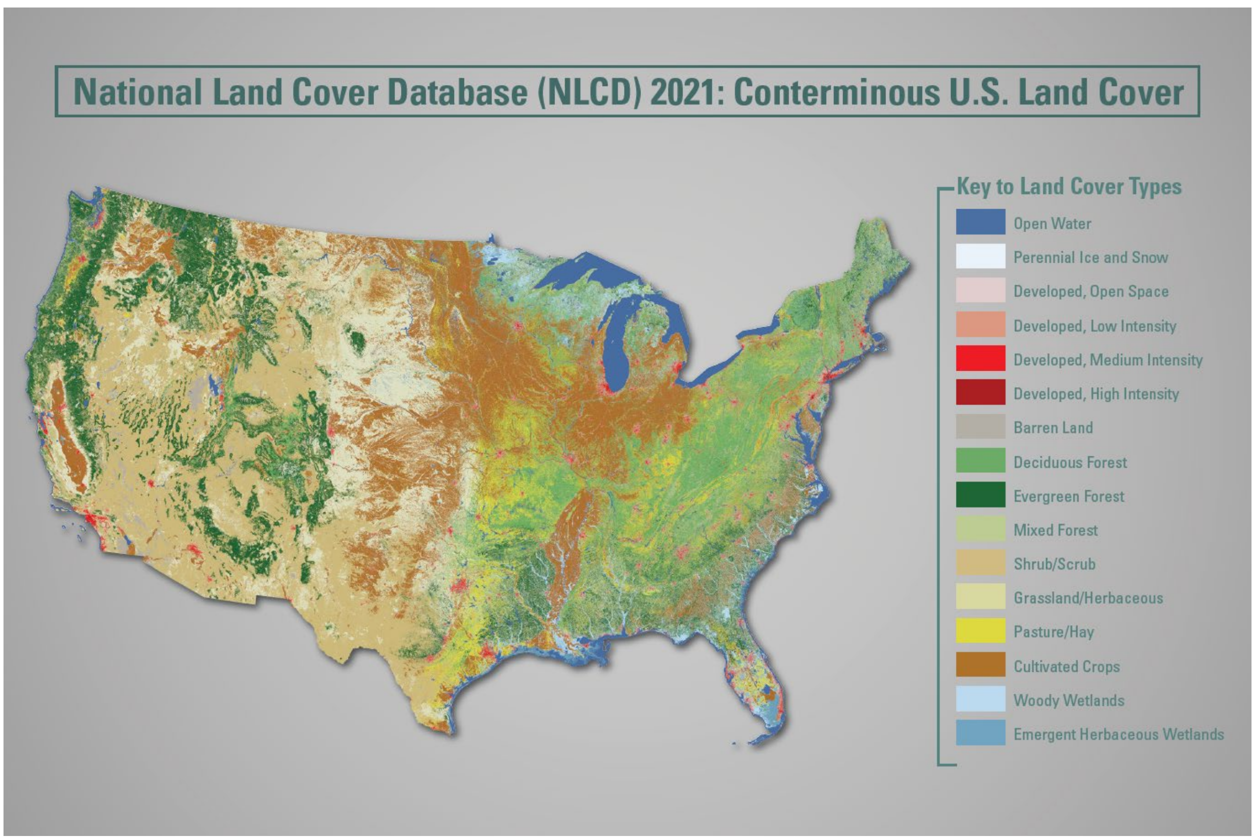

Figure 9. *Map of the Conterminous U.S. showing the land cover layer from the NLCD.*

USGS is currently working to combine the NLCD and LCMAP product lines and improve LULC data by increasing the accuracy of LULC mapping; improving the delivery of LULC data from the current 2-5 year interval to seasonal and annual time interval; innovating and delivering special LULC categories such as urban centers for GHG tracking purposes; linking with other land surface monitoring products such as those related to drought, water use, fire, rangeland condition and invasive grass mapping; and providing historical backcasting, short-term forecasts, and long-term projections based on climate and land use scenarios. It is also a goal of USGS to provide mapping of LULC data from first-generation (1970s) Landsat data.

NOAA's Coastal Change Analysis Program (C-CAP) is the coastal expression of NLCD and provides a more detailed inventory of coastal wetland types and their associated change through time. C-CAP data have been delivered every five years, since at least 1996, and have been the basis for the coastal wetland estimates within the U.S. GHG Inventory. NOAA is currently working to produce a higher spatial resolution (one-meter) set of land cover and change products that would be a replacement for the past 30-meter C-CAP and NLCD mapping in coastal areas. These data would provide more detailed change information in coastal regions, which would more accurately reflect the condition and types of change commonly seen in coastal wetlands. These data would also support more detailed analysis at the local level, including support for urban forestry and more detailed development tracking, and could be used to help improve national mapping at the coarser Landsat scale.

While current USG geospatial products provide important and useful data for informing and attributing GHG analyses, they are not always consistent in defining and mapping of LULC classifications. This presents a challenge when integrating/harmonizing multiple USG products into one analysis. Developing a guidance document of definitions for LULC classifications across different USG geospatial products and ground-based inventory systems could improve the efficiency in harmonizing data products and provide additional transparency to data users and the public. Specifically, agencies will collaborate to develop an approach for aligning LULC definitions and classifications across the USG and create a process for identifying new LULC classifications or subsets of existing classifications, as needed, to better characterize the wide variety of LULC classifications and conditions on federal, state, Tribal, and private lands. This task will also influence recommendations for characterizing routine land management activities that, while they may not change a land cover classification or land use type, can be used to develop land management practices in a way that will help reduce GHG sources and optimize sinks. Standard definitions and ways of organizing land management activities within land use types would help improve GHG estimates and with determining what sorts of activity data are needed to reflect management practices in GHG analyses.

Supporting Task: Increase accessibility and utility of datasets to support enhanced understanding and analyses of natural system fluxes.

Beginning in 2023, the U.S. GHG Center will publish datasets of natural fluxes for carbon dioxide and methane that capture different physical processes, take advantage of different observations, and allow users to track the impact of recent changes in sources and sinks. Initial datasets are derived from NOAA's CarbonTracker measurement and modeling system and NASA satellites. Agencies will collaborate to improve the quality, latency, and spatial resolution

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of estimates of natural sources and sinks. Incorporation of new datasets, including from other agencies, and time extensions of current ones will be phased in based upon stakeholder input.

Supporting Task: Integrate remote sensing data, in situ observations, science, and advanced modeling and statistics to improve characterization of GHG emissions and fluxes from forest ecosystems.

The USDA Forest Service is engaged in a burgeoning effort to align remotely sensed information, plot network observations, and biometric/ecosystem-process modeling for forest ecosystem monitoring, with the goal of producing reliable, annually updated data on forest biomass and other policy-relevant forest characteristics at spatial scales suitable to inform forest management. Emerging machine-learning and associated statistical procedures, coupled with data and code availability, allow for forest ecosystem GHG assessments to be produced at increasingly finer spatial and temporal scales, while empowering industries to meet environmental and social governance expectations via reduced emissions throughout supply chains. Given that this work is highly data-driven, advances across a variety of disciplines, federal agencies, and partners could be more efficiently facilitated by a federally curated clearinghouse of data, models, code, and associated technical documentation. Accelerating public/private R&D in the following areas would significantly improve GHG data and tools for forest management:

- Developing statistical procedures to incorporate a variety of data inputs for robust characterization of uncertainty.
- Timely delivery of forest plot network observations with refined models of tree volume/biomass, carbon fractions, and carbon pool models (including soil, coarse roots, stumps, and dead wood).
- Building out tree assessments outside forests (e.g., agroforestry and urban land uses).
- Refining land cover and use mapping through consideration of higher resolution imagery, including from USDA's National Agricultural Imagery Program (NAIP), in the context of Landsat baselines.
- Conducting forest structural assessments via stereo NAIP, radar (e.g., NASA-ISRO Synthetic Aperture Radar), and/or LiDAR platforms (e.g., NASA GEDI (Global Ecosystems Dynamics Investigation) instrument on the International Space Station).
- Incorporating climate and ecosystem process models derived from flux networks (e.g., NEON or AmeriFlux).
- Tighter coupling to communities and economies through the characterization of forest management with refined biometric modeling, forest stand projection systems, improved quantification of fire effects, and harvesting activities including residues and utilized wood.
- Coordinated collection of harvested wood product information to more accurately estimate product mixes, associated lifecycles, and final deposition (e.g., cradle to grave

accounting), such that emissions can be reduced along supply chains while empowering climate-smart landscape/architectural designs.

For existing strategic monitoring programs such as the Forest Service's FIA program, efficiencies have long been realized by incorporating auxiliary information derived from remote sensing into ground-based forest inventories and estimation, including estimates of uncertainty.[73] The FIA program has long partnered with other federal agencies. For example, FIA partners with NASA to conduct interior Alaska surveys, and FIA plots can be integrated with similar long-term forest plots operated by the Smithsonian Institution[rr] that are global in extent. FIA plot data, based on FIA survey protocols and models, are often used in validation/calibration exercises to ground-truth remote sensing observations and derived products (for example, NLCD). The Forest Service annually produces the Landscape Change Monitoring System national LULC product, which includes post-disturbance monitoring. Related products can also support estimation of emissions from wildfire.

The Forest Service will continue to develop and refine algorithms that combine aircraft- and space-based[ss] measurements of forests coupled with ground-based measurements from FIA plots to provide unbiased estimates of forest characteristics such as biomass, including estimates of precision, with fine spatial granularity across large spatial extents. Additionally, the FIA program is expanding work with academic and industrial partners to refine statistical approaches for downscaled forest GHG assessments collectively referred to as small-area estimation.

In addition to providing authoritative data and models to external entities to empower forest GHG assessment development and transparency, FIA is working towards automated production workstreams for creating biennial or more frequent nationwide, 30-meter or finer-scale estimates of each major carbon stock pool in forest ecosystems, with the aim of sufficient precision and accuracy to support management decisions.[tt] Advances in small-area estimation techniques and release of 30-meter or less geospatial products raise several considerations that must be addressed prior to full implementation. These include: 1) private landowner privacy concerns regarding fine-scale spatially explicit map products, 2) additional R&D to improve estimates and support data users, 3) targeted additional survey data to increase accuracy and precision to support management decisions, 4) compatibility with forest resource projection systems that inform project-level management options and large-scale policy considerations, and 5) long-term implementation and maintenance strategies.

FIA's approach to natural resource monitoring—combining ground-, aircraft- and space-based measurements with data synthesis, allometric equations, land cover mapping, and process models—can be applied to other ecosystem types. Natural resource monitoring systems

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[rr] The Smithsonian Institution's new GEO-TREES project provides a network of global biomass reference measurement sites with a common standard for high-quality data acquisition, transparent measurement protocols, long-term monitoring, and measurements traceable to standard units.

[ss] Including LiDAR, radar, and multi-spectral imagery.

[tt] FIA can currently produce 30-meter map products for any attribute in the FIA database (which includes estimates of major carbon pools), in approximately two weeks when refreshed inventory data are available as well as personnel.

incorporating this level of technical detail allow for more precise characterization of GHG emissions and sinks and should be further explored for various ecosystem types.

Phase II

Phase II of the GHGMMIS reflects a future iteration in which demonstrations and planning from Phase I enable a more capable, robust system for delivering high quality, authoritative data to support climate action at the local, state, Tribal, and national levels. Fundamental to Phase II is the implementation of a more robust, formalized coordination structure that leverages collective U.S. capabilities and expertise to realize the vision, goals, and objectives outlined in the National Strategy. In 2024, the Greenhouse Gas Measurement and Monitoring Interagency Working Group (GHG IWG), with input from non-federal entities, will begin to scope out this broader coordination structure. To the extent possible, the GHG IWG will leverage existing forums and coordination mechanisms, while recognizing that new or enhanced mechanisms to collaborate with external partners may be needed. As the U.S. GHG Center ramps up initial work, it is also expected to play a larger role in coordinating GHG data efforts and is likely to expand beyond the four initial agencies involved (NASA, EPA, NIST, NOAA).

A potential challenge in Phase II will be how to balance support for continuity of existing, high-value observing systems and capabilities while continuing to innovate and incorporate new measurement technologies and methods in response to technological advances, policy changes, or other factors. Addressing this challenge will require efficient use of resources and partnerships and clearer articulation of USG and non-USG roles and contributions. Additionally, the USG and external partners will need to have demonstrated a pathway to cost-effective scale up and sustained operations of GHGMMIS capabilities.

The National Strategy also recognizes the need for global GHG monitoring and interoperability between U.S. and global observing and data systems. Federal agencies are actively engaging in international forums that are discussing coordinated global GHG monitoring and international standards for GHG measurement. Phase II is expected to have more explicit connections between a U.S. GHGMMIS and a global GHG monitoring system.

IV. Conclusion

Numerous GHG measurement, monitoring, and data capabilities currently exist but are spread across various federal and non-federal entities. The Nation has the opportunity to enhance coordination and integration of these capabilities, make more efficient use of resources, and leverage recent scientific and technological advances to develop an integrated GHG measurement, monitoring, and information system that delivers more comprehensive, granular, and timely data to support climate action at local, state, Tribal, and national levels. The National Strategy outlines a vision, principles, objectives, and near-term demonstration areas to guide collective efforts, accelerate progress towards achieving ambitious U.S. greenhouse gas reduction goals, and demonstrate continued U.S. leadership in addressing the impacts of climate change.

Appendix–Acronyms

ANSI: American National Standards Institute

ARPA-E: Advanced Research Projects Agency–Energy

ARS: Agricultural Research Service

ATDM: atmospheric transport and dispersion models

C-CAP: Coastal Change Analysis Program

CEOS: Committee on Earth Observation Satellites

CH_4: methane

CO_2: carbon dioxide

COCCON: Collaborative Carbon Column Observing Network

DOC: Department of Commerce

DOD: Department of Defense

DOE: Department of Energy

DOI: Department of the Interior

DOS: Department of State

EPA: Environmental Protection Agency

FAIRER: Findable, Accessible, Interoperable, Reusable, Equitable, and Responsible principles

FIA: Forest Inventory and Analysis Program

GHG: greenhouse gas

GSICS: Global Space-based Inter-Calibration System

GHG IWG: Greenhouse Gas Measurement and Monitoring Interagency Working Group

iM4: Methane Measurement, Monitoring, and Mitigation

IPCC: Intergovernmental Panel on Climate Change

IRA: Inflation Reduction Act

ISRO: Indian Space Research Organization

ISO: International Organization for Standardization

LCMAP: Land Change Monitoring, Assessment, and Projection

LiDAR: Light Detection and Ranging

LULC: land use and land cover

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METEC: Methane Emissions Technology Evaluation Center

MMRV: measurement, monitoring, reporting, and verification

MSW: municipal solid waste

NAIP: National Agricultural Imagery Program

NASA: National Aeronautics and Space Administration

NGO: Non-governmental organization

NLCD: National Land Cover Database

N_2O: nitrous oxide

NOAA: National Oceanic and Atmospheric Administration

NRI: National Resources Inventory

NSF: National Science Foundation

OSMRE: Office of Surface Mining Reclamation and Enforcement

PSM: primary gas standard mixtures

QA/QC: quality assurance/quality control

R&D: Research and development

SF_6: Sulfur hexafluoride

SI: International System of Units

SOC: Soil Organic Carbon Monitoring and Research Network

STAR: Science to Achieve Results Grant program (EPA)

SWIR: short wave infrared

TCCON: Total Carbon Column Observing Network

USG: U.S. government

USGCRP: U.S. Global Change Research Program

USGS: U.S. Geological Survey

WMO: World Meteorological Organization

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