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Federal Strategy to Advance Greenhouse Gas Emissions Measurement and Monitoring for the Agriculture and Forest Sectors

Presented by the Greenhouse Gas Monitoring & Measurement Interagency Working Group

Executive Summary[1]

This report outlines a draft framework for measurement, monitoring, reporting, and verification of greenhouse gas (GHG) emissions and removals for the agriculture and forest sectors, as part of a larger strategy to advance an integrated U.S. greenhouse gas monitoring & information system.[2] This work builds on the ongoing Federal work to produce the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. GHG Inventory) and other GHG analyses. It also takes advantage of advanced measurement and modeling capabilities, as well as the growth of GHG observational data, to improve and verify estimates and provide enhanced data products. Net agricultural emissions now represent roughly 10 percent of U.S. GHG emissions,[3] while the forest sector remains a net sink of GHGs across the 1990-2021 time series[4]; hence, agriculture and forests offer critical mitigation opportunities. Any comprehensive GHG monitoring effort will need to consider GHG emissions and removals from the agriculture and forest sectors to advance efforts to stabilize Earth's climate. This report articulates near-term activities and projects that address known needs and gaps in our current GHG emissions measurement and monitoring capabilities. Strategic priorities for improving the measurement, quantification, and verification of GHGs within the agriculture and forest sectors include the following:

- Invest in science and research that improve our understanding of GHG emissions and sinks in response to changes in inputs, management activities, and environmental factors;
- Reduce uncertainty and improve accuracy of models, methods, and tools used to estimate GHGs;
- Improve data and data products used in quantifying GHG sources and sinks;
- Accelerate the incorporation of new data and information into GHG estimates, including data and information from non-Federal sources;
- Improve monitoring and verification of GHG emissions and sinks from agricultural activities and forests;
- Improve accuracy of the U.S. GHG Inventory through improved science, models, and data; and
- Synthesize GHG estimates into actionable reports and analyses.

Activities and projects identified by agencies that can address these strategic priorities include:

- Establishing a climate-smart forestry decision support system to support MMRV activities in the forestry sector;
- Operationalizing a national soil carbon monitoring network;
- Improving soil carbon measurement methods, technology, and cost-effectiveness;

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[1] The GHG IWG is releasing this report as a draft for public comment (see instructions for RFI at **https://www.regulations.gov/docket/USDA-2023-0009**)

[2] This report is a companion document to the draft *Federal Strategy to Advance an Integrated U.S. Greenhouse Gas Monitoring & Information System,* which was released for public comment in February 2023.

[3] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[4] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

- Establishing GHG research networks to better coordinate and synthesize GHG research on crop and livestock systems;
- Improving collection and accessibility of conservation activity data related to crop and livestock systems;
- Improving tracking and reporting of GHG emissions from wildfire;
- Estimating and mapping forest biomass;
- Improving mapping of land conditions in support of national GHG quantification activities; and
- Accelerating adoption of applications and tools that support climate-smart agriculture and forestry.

I. Introduction

The United States has established a commitment to achieve 50 to 52 percent reduction from 2005 levels in greenhouse gas (GHG) emissions by 2030 and achieve economy-wide, net-zero emissions by 2050. In support of this and other Administration goals, in January 2022, the White House established the Greenhouse Gas Monitoring & Measurement Interagency Working Group to coordinate and accelerate Federal efforts to enhance measurement and monitoring of GHG emissions and removals from the atmosphere. Agencies have begun collaboration on two workstreams-–one focused on a broader framework for an integrated U.S. GHG monitoring and information system[5] and one focused more narrowly on the agriculture and forest sectors, given the importance of, and unique monitoring and measurement challenges associated with, these sectors.

The framework and strategy outlined in this document are meant to provide a roadmap for improving measurement, monitoring, reporting, and verification (MMRV) [6] in the agriculture and forest sectors. This will, in turn, support: (1) identifying opportunities to reduce emissions, and thereby accelerating progress towards U.S. climate goals; (2) holistically evaluating effects of changing land cover and land use, and management practices on GHG fluxes; (3) determining the impacts of disturbance events such as wildfires and droughts on net emissions and carbon stocks; (4) assessing U.S. progress towards its emissions goals, including through the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*[7] (U.S. GHG Inventory) and the U.S. Nationally Determined Contributions (NDC) for the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement; and (5) measurement and confirmation of field-scale carbon sequestration and GHG emissions removals through implementation of climate-smart agricultural and forestry practices. An effective MMRV strategy for the agriculture and forest sectors will improve estimates at the national, regional, and entity[8] scales, while also improving confidence in the GHG benefits of mitigation activities, reducing uncertainty, and maintaining trust in emissions data.

The agriculture and forest sectors, as defined in this strategy, include GHG emissions and sinks from cropland, grassland, livestock, and forests[9], such as:

- Cropland: Soil carbon, ecosystem carbon stocks[10] from forest land transitioning to cropland, agricultural soil management nitrous oxide (N_2O) emissions (direct and

[5] In February 2023, the GHG IWG released an RFI for the draft *Federal Strategy to Advance an Integrated U.S. Greenhouse Gas Monitoring & Information System* (see RFI materials at https://go.nasa.gov/USGGMIDraftFederalStrategy). The public comment period for that RFI ended on April 19.

[6] Measurement, Monitoring, Reporting, and Verification (MMRV) refers to activities undertaken to quantify GHG emissions and sinks (through direct measurement and/or modeling), monitor emissions over time, verify estimates, and synthesize and report on findings.

[7] https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

[8] Agricultural entity means a farm, ranch, or corporation engaged in growing, harvesting, or handling of crops, natural fibers, fruits, vegetables, plants, or trees, or feeding or care of livestock, poultry, or fish.

[9] The U.S. GHG Inventory includes emissions and removals from Agriculture and Land Use, Land Use-Change, and Forestry; collectively, this sector is also referred to the Agriculture, Forestry and Other Land Uses (AFOLU) sector. Greenhouse gas emissions and removals from the AFOLU sector include those coming from croplands, grasslands, livestock management and forestry related to this strategy. AFOLU also includes emissions and removals from other land uses such as wetlands and settlements that are not included in this MMRV strategy but are being discussed as part of the GHG IWG's efforts.

[10] Includes aboveground biomass, belowground biomass, dead wood, litter, and soils (mineral and organic).

indirect), methane (CH_4) from rice cultivation, CH_4 and N_2O from residue burning, and carbon dioxide (CO_2) from urea fertilization and liming.

- Grassland: Soil carbon, ecosystem carbon stocks from forest land transitioning to grassland, agricultural soil management N_2O emissions (direct and indirect), and grassland fires.
- Livestock: CH_4 from enteric fermentation, CH_4 and N_2O (direct and indirect) from manure management, and CH_4 from grazed lands.
- Forests: Carbon in aboveground biomass, belowground biomass, dead wood, litter, mineral soils, organic soils, and harvested wood products (products in use, and in solid waste disposal systems), N_2O emissions from mineral soils, and non-CO_2 emissions from forest fires and drained organic soils.

This report outlines framework elements needed to accurately quantify GHGs from agriculture and forests, as well as near-term approaches and strategies that will improve accuracy and reduce uncertainty in GHG estimates and provide timely public reporting of GHG emissions and removals. This report will inform a new agriculture and forest section of the *Federal Strategy to Advance an Integrated U.S. Greenhouse Gas Monitoring & Information System*, a draft of which was released for public comment in February 2023[11].

II. Challenges to Quantifying GHGs in the Agriculture and Forest Sector

Federal agencies maintain a broad array of capabilities to estimate and measure, monitor, and verify agriculture and other land-use activities and the associated GHG emissions and removals at various scales and from various sources. A great deal of interagency cooperation exists to prepare GHG analyses, in particular the annual U.S. GHG Inventory, and to identify and conduct research and assessment on improvements to these GHG estimates (see Box 1 for more details on how the U.S. GHG Inventory is compiled). Given its comprehensive nature, the U.S. GHG Inventory provides one way to organize MMRV efforts and provide the requirements (e.g., spatial scale, accuracy, latency, time series) that inform agency research, technology, and observation capabilities. The U.S. GHG Inventory also provides a good starting point for identifying known capabilities, gaps, and challenges related to measurement and monitoring of GHGs in the agriculture and forest sector.

The agencies contributing to this strategy recognize the need to expand cooperation to take advantage of new opportunities for improving measurement and monitoring of GHGs from agricultural activities and forests, including leveraging expertise and resources from academic, commercial, and non-profit partners. Agencies have identified key challenges to quantifying GHGs from the agriculture and forest sector, which include:

- Many of the source and sink categories within the agriculture and forest sectors are complex and heterogeneous, making GHG quantification challenging. The coverage and quality of GHG measurement and quantification varies across source categories,

[11] The draft *Federal Strategy to Advance an Integrated U.S. Greenhouse Gas Monitoring & Information System* did not discuss emissions from the agriculture and forest sectors.

Box 1. Compiling the U.S. Greenhouse Gas Inventory

The U.S. GHG Inventory provides a national-level annual reporting of anthropogenic sources and sinks of GHGs from 1990 to present and is the metric by which the U.S. nationally determined contribution (NDC)—the United States' commitment to reduce national emissions under the Paris Agreement—is assessed. In addition, the Inventory is a valuable resource that can help identify emissions reduction opportunities and inform cost-effective policy options. The U.S. Environmental Protection Agency (EPA) is responsible for preparing the U.S. GHG Inventory and coordinating the multidisciplinary team of government agencies, researchers, and contractors that contribute to the U.S. GHG Inventory each year.

The Agriculture and Land-Use, Land-Use Change and Forestry (LULUCF) chapters of the Inventory—also referred to collectively as the Agriculture, Forestry, and Other Land Use (AFOLU) sector—estimates emissions and removals of multiple gases across numerous agricultural and land use activities. This is done by estimating the carbon stock changes from each of the five carbon pools (aboveground biomass, belowground biomass, dead organic matter, litter, soil) and non-CO_2 gases for each of the 36 land-use conversion categories. The AFOLU sector estimates rely heavily on cooperation, data, and models from the U.S. Department of Agriculture (USDA), the USDA Forest Service, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geologic Survey (USGS), in addition to many other supplemental data sources. Of particular importance are activity data from the National Resources Inventory (NRI), Forest Inventory and Analysis program (FIA), Census of Agriculture, Conservation Effects Assessment Project (CEAP) cropland farmer survey, the Agricultural Resource Management Survey (ARMS), the USDA National Agricultural Statistics Service (NASS), and other conservation activity datasets.

geographies, and scales. For example, there is a lack of data on application rates and timing of nitrogen fertilizer additions to soils, water management practices for rice production, animal diets, and perennial biomass data on croplands and grasslands. In other cases, quantification methods may be coarse where models lack the ability to characterize and disaggregate certain emission sources to more specific activity drivers, which can in turn necessitate the use of simpler estimation approaches; these often are not able to reflect ongoing GHG mitigation activities or impacts from changes in management practices. Improving data, science, research, and modeling where there are known gaps is instrumental to improving accuracy and reducing uncertainties of our GHG estimates from agriculture and forests.

- Current GHG MMRV capabilities have evolved over time and heavily leverage work that may have been prepared for other purposes (e.g., NRI, FIA, USDA Natural Resources Conservation Service (NRCS) program data, etc.). Many of these data collection capabilities were not designed to support long-term operational support of GHG MMRV activities. As a result, data interpolation between different data sources and/or assumptions based on expert opinion are often necessary to generate time series data that suit estimation needs.

- While agencies recognize the need to share and access data across multiple agencies to advance agency abilities to develop, test, implement, and visualize new data sources, models, technologies, and remote-sensing capabilities, agencies often lack the ability to easily share data, particularly data that include personally identifiable information (PII) or

confidential business information (CBI), and where data sharing may be constrained by statute and regulations.

- Monitoring and reporting land use and land conversions requires sustained observation networks that are maintained over time, since strategic-scale reporting and international policies require long-term baselines (e.g., UNFCCC 1990 baseline for U.S. GHG Inventory reporting). Existing systems, such as the FIA and NRI, meet some existing needs but are often not sufficient for supporting all relevant policy goals. Earth observation data have the potential to advance MMRV capabilities in the agriculture and forest sector, but in many cases, they are not adequately integrated or leveraged in current MMRV efforts.

- Timeliness and completeness of management and conservation activity data (i.e., data representing the extent to which a human activity takes place, such as livestock populations, fertilizer applications, etc.) needed to support annual GHG estimations is lacking across most major source and sink categories in the agriculture and forest sectors. Opportunities to improve completeness, timeliness, and quality of these data include improving existing surveys, developing new surveys, utilizing non-Federal data where appropriate, and better use of Earth observation data.

- Remote-sensing technologies and data products (e.g., above-ground biomass, cover crop and tillage data products) developed both inside and outside of the U.S. Government have demonstrated the potential to lower costs, improve quality, reduce uncertainty, and reduce timelags in generating GHG inventory information. Many of these capabilities (e.g., soil/litter/detritus mapping, airborne remote sensing of methane from livestock operations) are still at lower levels of application/operations and technology readiness. Maturing these technologies and transitioning them to operational use may pose challenges due to limited capacity to absorb new applications and technologies in operational agencies, the need to develop standards and protocols so that capabilities can scale efficiently, and the time and resources required to develop training and support material when new processes and information are used.

- There has been robust basic and applied research on understanding the processes and drivers of emissions and sequestration in the agriculture and forest sector. This research continues to expand in both scope and specificity but varies in maturity depending on the source category, requiring strategic investments in research to fill knowledge gaps.

- There are often challenges related to transitioning mature research efforts to operational status. This requires greater coordination and synthesis of research findings across and within agencies in a way that makes them useful for informing mitigation strategies, improving models and estimates, and reducing uncertainties.

- While there have been national programmatic frameworks in the past where soil carbon has been measured at designated locations (e.g., the Rapid Carbon Assessment (RaCA)), there is currently no ability to systematically monitor soil carbon over time for agricultural systems. A national framework consisting of designated sampling locations on private lands where soil carbon can be measured across time, and agricultural site

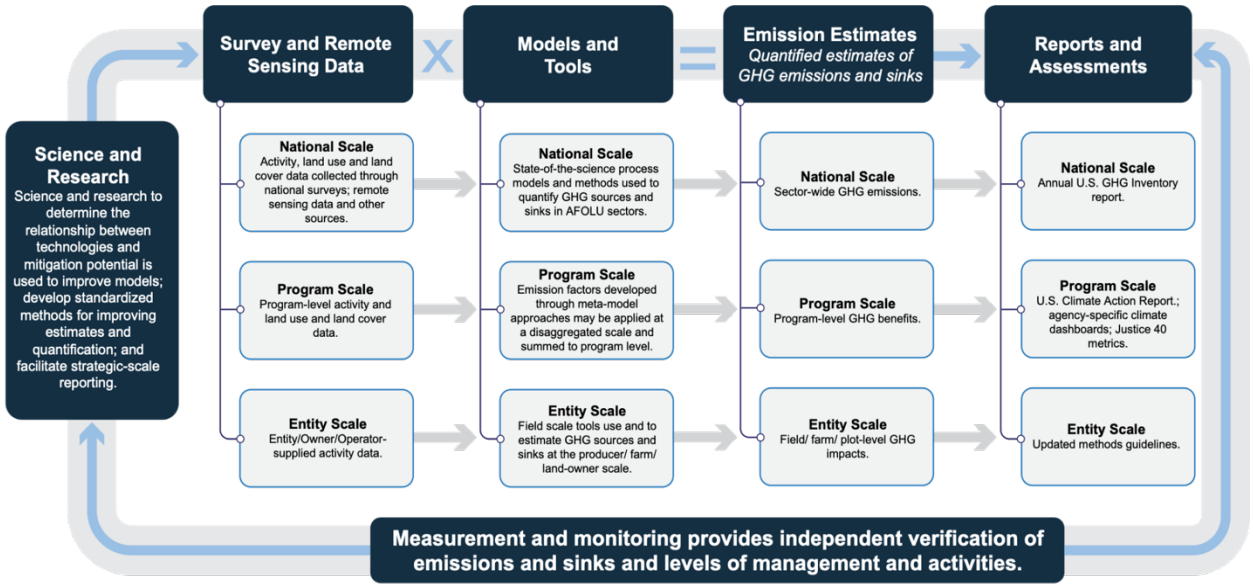
history documented, is much needed. Associating agricultural practice with measured soil carbon change over time can accelerate adoption of the most effective practices, support the Administration's policy goals, and inform, support, and improve the U.S. GHG Inventory.

III. A GHG MMRV Framework for the Agriculture and Forest Sectors

This section presents a GHG MMRV framework that identifies and combines five elements necessary for the comprehensive measurement, monitoring, reporting, and verification of GHGs in the agriculture and forest sectors (including the cropland, grassland, livestock, and forest sources and sinks described in Section I). The framework elements are: (1) scientific research to characterize GHG sources and sinks, as well as mitigation measures; (2) data and data products (including land use, environmental, and land management and activity data derived from surveys and remote sensing data); (3) models, methods, and tools used to estimate GHG sources and sinks from agriculture and forests; (4) monitoring and verification activities to monitor and confirm changes in GHG sources and sinks (e.g., soil carbon stocks); and (5) reports and assessments that synthesize and convey GHG data in a way that is policy-relevant and easy to access.

The framework (Figure 1) illustrates how land use, management, and conservation activity and other data can be paired with models, tools, or modeling outputs to generate GHG emission estimates at the national scale, sub-national or programmatic scale, and entity or field scale. These GHG estimates can subsequently be used for reporting and analyses, including projections that explore how emission trends are linked to changes in land use, management, or other factors. Data, models, and estimation methods used to quantify GHG sources and sinks are underpinned by science and field-scale research that not only help describe the relationship between GHG sources and sinks and landscape and activity data, but also help calibrate and validate these models. Finally, direct measurement and monitoring of GHG emissions and sinks provides a valuable independent way of verifying bottom-up estimates at various scales while informing new sensor/data development that can in turn help refine estimates. Direct measurements may also be used to assess specific climate-smart practices that are generating the GHG benefits upon which government or third-party payments are being made. On a larger scale, *in situ* measurements can help calibrate and refine data products derived from Earth observation (EO) data, leading to more accurate estimates.

Figure 1. A Framework for GHG MMRV in the Agriculture and Forest Sectors at Relevant Scales.



Agencies within the GHG IWG developed and used this framework as a guide to identify and prioritize areas within each framework element where investments could lead to overall improvements in GHG quantification within the agriculture and forest sectors. By strengthening monitoring, research, data, models, and tools, we can improve accuracy and reduce uncertainty in estimates of GHG sources and sinks from agriculture and forests. Better GHG estimates will in turn strengthen reporting, analyses, and projections related to GHG sources and sinks in the agriculture and forest sectors. Section IV below outlines priority improvements within each of the framework elements.

IV. Strategic Priorities for Improving MMRV of GHGs in the Agriculture and Forest Sectors

Based on current capabilities, gaps, and challenges to measuring and monitoring GHGs from agriculture and forests (as identified in Section II), agencies identified several strategic priorities within each framework element. These strategic priorities represent areas where targeted agency action and investments could improve MMRV capabilities and accelerate the development of a comprehensive MMRV strategy across agencies. Below are the strategic priorities identified under each element of the framework.

A. Science and Research

Strategic goal: Invest in science and research that will advance the ability of the U.S. Government to accurately quantify GHG sources and sinks at the national, subnational, and field scales with an emphasis on field-based research to improve our understanding the impacts of management and environment on GHG fluxes; development of technologies to accurately quantify GHG emissions and/or soil carbon; and advancement of methods and understanding of

the relationships between EO data and agriculture and forestry activities and impacts. Priorities include:

- Improve consistency and transparency in how climate-smart agriculture and forestry practices and related technologies are evaluated and how research data are collected, stored, and shared. This will in turn allow for easier comparison and meta-analyses across research projects, and facilitate integration of findings into quantification methods, models, and tools.

- Invest in science and research to improve our understanding of GHG fluxes (including N_2O, CH_4, and CO_2) in response to crop, grassland, livestock, and forestry management activities as well as regional and environmental variables.

- Improve our ability to use EO data to identify activities (e.g., tillage) and/or estimate environmental variables (e.g., burned areas) critical to GHG estimates. EO data can also measure quantities such as surface soil moisture, which can inform and enhance estimates of GHG fluxes.

- Reduce the cost and improve the reliability of *in situ* soil carbon measurements for use in soil carbon monitoring systems.

- Improve communication and coordination among agencies on relevant research and technology needs and developments.

B. Models, Methods, and Tools

Strategic goal: Improve models, methods, and tools used to estimate GHG sources and sinks at the national, subnational, and field scales to reduce uncertainty and improve accuracy of GHG estimates. Priorities include:

- Improve accuracy and reduce uncertainty of models by coupling them with field-level observations to ground-truth and validate results, as well as improve model parameterization. Model improvements will rely heavily on data from field research on GHG fluxes within the agriculture and forest sectors (including those from agricultural soils, flooded rice cultivation systems, livestock emissions, and forest carbon stocks) to parameterize and validate models across a range of management practices and regional variations. Remotely sensed data can also improve model results by constraining quantities relevant to GHG fluxes.

- Continuously improve model processes (e.g., carbon and nitrogen cycle processes) and update estimation methods to reflect state of the science. Investments in strategic research to improve our understanding of GHG fluxes in soils, above- and below-ground biomass, rice cultivation, and livestock emissions will ultimately help reduce uncertainty within our models by improving their accuracy and ability to estimate GHG fluxes in the agriculture and forest sectors.

- Invest in new or improved decision-support tools that provide GHG estimates and/or projections at the field, programmatic, or national scales under different scenarios.

- Enhance model intercomparisons and analyses to improve our understanding of system dynamics and improve model performance.

- Increase coordination across agencies on model and tool development and improvements.

C. Data and Data Products

Strategic goal: Improve the data and data products (including land use, environmental, and land management and conservation activity data) used to quantify GHG sources and sinks at the national, subnational, and field scales in order to improve timeliness and accuracy of GHG estimates. Priorities include:

- Improve alignment of EO data, data products, and data platforms with the needs of GHG quantification efforts in the agriculture and forest sectors (e.g., ensuring that production of data and data products is sustained over time, invest in development of data products that can enhance timeliness and accuracy of GHG estimates, etc.).

- Better integrate EO data into GHG quantification efforts to improve timeliness and accuracy of GHG estimates. For example, integrate remote-sensing products for cover crop and tillage, burned areas, and evapotranspiration into agriculture and forest sector MMRV efforts to improve coverage, accuracy, and timeliness of estimates.

- Improve use of data from non-Federal sources, where available and appropriate, within GHG estimates. For example, industry data on animal feed composition, use of feed additives, and anaerobic digesters might be able to supplement data from surveys, government programs, and remote sensing to make more accurate GHG estimates. Also, private-sector measurements of soil carbon are a potentially valuable resource for understanding relationships between practices and soil carbon storage.

- Improve timeliness, reduce latency, and fill gaps in the activity data collected through surveys and used in GHG estimates. For example, expand collection of relevant data on manure management systems, grazing practices, animal diets, soil amendments, and enhanced efficiency fertilizers through existing USDA surveys like the Census of Agriculture, National Animal Health Monitoring System (NAHMS), CEAP and ARMS.

- Improve coordination across agencies on data and resource sharing, as well as develop coordinated responses to shared data needs.

D. Monitoring and Verification

Strategic goal: Improve ability to monitor GHG fluxes and verify GHG estimates at the national, subnational, and field scales. Priorities include:

- Establish a soil carbon monitoring network to track and monitor soil carbon and N_2O dynamics in agricultural and forest lands over time.

- Improve collection and accessibility of measurement and monitoring data, especially those data gathered from long-term monitoring sites, to help verify GHG estimates, improve models, and reduce uncertainty, and verify field-scale activities and outcomes.

- Establish verification protocols at national, subnational, and field scales to support consistent and accurate GHG estimates and potentially reduce MMRV costs over time.

E. Reports and Analyses

Strategic goal: Use MMRV activities at national, subnational, and field scales to support timely and accurate synthesis of GHG data into actionable information, promote transparency, and meet reporting obligations. Priorities include:

- Explore options to establish centralized data systems and visualization tools that would aggregate and disseminate data from multiple sources.

- Develop data products and reports that improve the usefulness and accessibility of GHG estimates at the national, subnational, and field scales to support decision-makers.

- Improve the ability of the U.S. GHG Inventory to reflect activities within the agriculture and forest sectors through integration and synthesis of improved data and models developed through this MMRV strategy to better reflect national investments and support international commitments in line with UNFCCC and IPCC requirements.

V. Sector Plans for Improving MMRV

The policy-related goals outlined in the Introduction necessitate a comprehensive plan to enhance MMRV of GHG emission and removals from the agriculture and forest sectors. Agencies are currently in the process of developing plans for improving MMRV of GHGs within the agriculture and forest sub-sectors (croplands, grasslands, livestock, and forests) based on the strategic priorities outlined above. Plans will address how elements of the framework can be strengthened and improved. Broad outlines of these plans are described below. In addition, the following section, Section VI, outlines several near-term activities and projects that will be integral to these plans moving forward. Once finalized, the sector plans will address the following key elements:

- Technical approaches, by sector, to improve GHG MMRV and develop comprehensive estimates of emissions and removals at entity, program, and national scales;
- Linkage of changes in land use, management, or other significant factors with emissions;
- Research priorities to close key technical gaps;
- Data accessibility for the public, with updates provided in line with sectoral needs;
- Intersectionality with private sector and academic efforts; and
- Strategies to account for uncertainties in GHG emissions data from the agriculture and forest sector.

Improving MMRV of GHG Sources and Sinks from Croplands and Grasslands

- **Science and research.** USDA plans to establish strategic research networks to perform research and synthesize findings on critical processes, including soil carbon dynamics, rice methane emissions, and N_2O from soils. The National Aeronautics and Space Administration (NASA) plans to leverage GHG research and existing partnerships to advance both the science and the applied research to monitor GHG emissions and/or practices while providing tools and data that help support the implementation of these practices (e.g., efficient nitrogen management, yield impacts, etc.).

- **Models, methods, and tools**. USDA and EPA plan to improve processes as well as calibration and validation of the DayCent model (the model used to estimate soil carbon and N_2O in the U.S. GHG Inventory) and continue to update the *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* report (Methods report) using data and outcomes from emerging research and the soil carbon monitoring network. NASA will work collaboratively with the private sector, Government agencies (e.g., EPA, USDA), and the research and modeling community to assimilate EO data into current and new models and develop an intercomparison framework for models to be evaluated using a multi-model ensemble modeling approach. NASA will also continue to work cooperatively with USDA and others on tools such as Crop-CASMA (Crop Condition and Soil Moisture Analytics) and VegScape (Vegetation Condition Explorer).

- **Data and data products**. USDA plans to improve its surveys to capture more timely and relevant information on cover crops, tillage, nutrient management, residue management, and rice irrigation practices. In addition, USDA, EPA, and others plan to collaborate with NASA to identify EO data products that can provide timely and relevant data for quantification of GHGs from croplands and grasslands. In addition, NASA will continue to develop and support data products such as those used to estimate evapotranspiration, delineate field boundaries, and estimate field sizes and changes over time, as well as advance the development of other essential agriculture variables (EAVs) developed under NASA's Global Agricultural Modeling (GEOGLAM) program. USGS and other collaborating agencies also plan to continue to improve national land cover data, which are used for national GHG estimates, with remote sensing data.

- **Monitoring and verification**. USDA plans to establish a soil carbon monitoring network to monitor soil carbon changes over time (see Section VI for details). These data can be used to parameterize soil carbon models, validate U.S. GHG Inventory estimates, train remote-sensing data products, and analyze the effectiveness of climate-smart practices, among many other uses.

- **Reports and analyses**. EPA plans to use improved survey data, remote-sensing products, and models to generate more accurate estimates for the U.S. GHG Inventory report. USDA will continue to use these data for reporting, projections, and other analyses.

Improving MMRV of GHG Emissions from Livestock

- **Science and research.** USDA plans to establish strategic research networks to perform research and synthesize findings on GHG emissions from the livestock sector, including enteric fermentation, manure management emissions, and grazing lands. NASA will explore opportunities to support USDA efforts, including leveraging NASA-funded research and observing systems to advance both the science and the applied research to assess and quantify GHG emissions from livestock operations.

- **Models, methods, and tools.** USDA and EPA plan to improve processes as well as calibration and validation of livestock models and methods (e.g., the Cattle Enteric Fermentation Model (CEFM), and the Methods report) using data and outcomes from livestock research networks.

- **Data and data products**. USDA plans to improve its surveys and identify where industry data can be used to capture more timely and relevant information on manure management, anaerobic digesters, animal diets, and grazing activities.

- **Monitoring and verification**. NASA has begun evaluating new approaches to measure methane from large point sources (including livestock sources) at finer spatial scales through the EMIT instrument aboard the International Space Station (ISS). NASA will also continue to evaluate the capabilities of commercial methane products to investigate their utility for augmenting NASA-collected methane concentration data in the future (e.g., tasking commercial satellites to observe identified hot spots at a finer spatial resolution). Methane data from Federal and commercial observing systems can potentially provide verification and validation for bottom-up methane estimates in the agriculture and forest sectors, as well as identify national methane emission hotspots and patterns that can help the U.S. Government identify and target mitigation opportunities.

- **Reports and analyses**. EPA plans to use improved survey data, remote-sensing products, and improved models to improve the U.S. GHG Inventory report in order to generate more accurate estimates. USDA will continue to use these data for reporting, projections, and other analyses.

Improving MMRV of GHG Sources and Sinks from Forests

- **Science and research**. Through its science and research programs, USDA Forest Service will work to improve understanding of forest dynamics including non-live tree carbon pool (soil, litter, dead wood, belowground, and stump) responses to environmental factors such as drought, fire, diseases, and management interventions (such as avoided deforestation, type conversions, or adaptive management), as well as lateral transfers among pools and other land uses.

- **Models, methods, and tools**. USDA Forest Service will work to improve stand simulation models to assess GHG effects of climate-smart forest management practices

(e.g., Forest Vegetation Simulator (FVS)) as well as ensure that forest carbon estimation methods as outlined in the Methods report reflect the state-of-the-science.

- **Data and data products.** USDA Forest Service will use remote-sensing data products from Federal and non-Federal sources to estimate forest carbon fluxes, for example, forest biomass maps, and fire data products.

- **Monitoring and verification**. USDA Forest Service plans to reduce the uncertainty and increase spatial/temporal granularity associated with forest GHG dynamics via joint optimization of its monitoring network (e.g., increasing sampling intensity and/or reducing cycle length on FIA plots while expanding the sampling of non-live tree carbon pools such as soil/litter and/or dead wood carbon) and application of concurrent research efforts to develop statistically rigorous small area estimation (SAE) with partners as directed by Public Law 117-328, the Consolidated Appropriations Act, 2023.

- **Reports and analyses.** EPA plans to use improved survey data, remote-sensing products, and improved models to improve the U.S. GHG Inventory report in order to generate more accurate estimates. USDA Forest Service will also work with USGS to better track and report emissions from wildfires.

VI. Proposed Near-Term Activities and Projects for Improving MMRV in the Agriculture and Forest Sectors

Federal agencies will collaborate on projects or initiatives that will help address strategic priorities identified by the agencies, implement elements of the sectoral MMRV plans, and advance the timeliness and accuracy of GHG estimates in the agriculture and forest sectors. In many cases these initiatives amplify ongoing government activities and will require deeper coordination among agencies, research partners, and the private sector. The timeline and scope for implementation of demonstration projects and initiatives will be contingent on the availability of resources. Additionally, agencies that received funding from the 2022 Inflation Reduction Act (IRA) are exploring how that funding may be used to help implement some of the activities described in this section. For example, USDA received $300M from the IRA (Section 21002(a)(2)) to "carry out a program to quantify carbon sequestration and carbon dioxide, methane, and nitrous oxide emissions" from agricultural sources. These funds will be used, in part, to undertake some of the USDA-led activities identified below for improving MMRV.

Proposed activities and projects for improving MMRV in the agriculture and forest sectors include:

1. National Soil Carbon Monitoring Network

Proposed implementing agencies: USDA

Subsectors addressed: Cropland, grassland

USDA will establish a national Soil Carbon Monitoring Network to monitor soil carbon changes over time across the agriculture landscape. As part of this effort, USDA will prepare and publish

standardized protocols for soil testing and sampling methods. USDA will apply these methods across a network of monitoring sites, create a database of soil data, 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 statutes. USDA has initiated a pilot monitoring, assessment, and evaluation (MAE) program through the Conservation Reserve Program (CRP). This effort will contribute to the Soil Carbon Monitoring Network. The Network will build the evidence base for investment in the adoption of climate-smart practices, as well as help to calibrate models that are used to estimate GHG fluxes for the U.S. GHG Inventory. The Network could utilize advances in soil carbon measurement technologies being developed by USDA Agricultural Research Service (ARS), the Department of Energy (DOE), and others.

2. Soil carbon measurement technology evaluation

Implementing agencies: USDA, DOE

Subsectors addressed: Cropland, grassland, forest

Soil carbon measurement technologies range from traditional soil core sampling to remote-sensing techniques, to more recent *in situ* technologies that can quickly assess soil carbon without the need to take soil samples. Given increased need for soil carbon measurements to improve MMRV, it is imperative to identify accurate, low-cost solutions that can meet agency objectives. USDA, through its ARS, and DOE, through its ARPA-E (Advanced Research Projects Agency-Energy) program, are investing in technologies to measure and monitor soil carbon. Under this demonstration project, 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 Soil Carbon Monitoring Network and to potentially address other soil carbon monitoring goals across the U.S. Government.

3. Improving conservation activity data

Proposed implementing agencies: USDA, NASA

Subsectors addressed: Cropland, grassland, livestock

USDA has identified several areas where the Department lacks comprehensive and timely data on national conservation practice adoption trends. These data are needed to adequately reflect changes in GHG emissions within the agricultural sector and are critical to informing the U.S. GHG Inventory and assessing progress toward the NDC. Data on tillage, cover crops, and nutrient management have moderate temporal gaps and often lack information on key management details. Data on livestock manure management, feed composition, and feed additives, agroforestry, and pasture/range practices have major temporal and practice detail gaps. To address these shortcomings, USDA is planning improvements to existing surveys, accelerated collection and release of data, alignment of statistical methods, better use of Earth observation data, use of non-Federal data sources, and new surveys. Particular focus will be in the following areas: crops and nutrient systems; grazing and pasture lands; silvopasture practices/agroforestry; livestock manure management, feed composition, perennial vegetation on cropland and grassland; and feed additives.

4. Agricultural GHG research networks

Proposed implementing agencies: USDA

Subsectors addressed: Cropland, grassland, livestock

USDA plans to align research on methane and nitrous oxide emissions from cropland, grasslands, and livestock sources through coordinated research networks of field measurements. Research networks would establish protocols for conducting measurement of GHG emissions (CO_2, N_2O, and CH_4) and mitigation with the aim of generating comparable and systematic data on the impacts of management and conservation activities on GHG fluxes on cropland and livestock operations. The research networks will inform conservation planning and create cohesiveness across related/complementary efforts. Areas of emphasis will include technologies such as enhanced efficiency fertilizers, feed additives, manure management systems, biogas, organic soils, and intensive rotational grazing. There will be an added emphasis on understanding impacts of technologies related to reducing methane emissions from enteric fermentation and GHG emissions from manure management systems.

5. Climate-smart forest carbon decision support system

Proposed implementing agencies: USDA Forest Service, USDA NRCS, NASA, USGS

Subsectors addressed: Forestry

Overall, significant opportunities exist to build upon surveys foundational to U.S. forest resources in terms of expanded scientific endeavors, public/private tool development, and increased empirical observations (both *in situ* and remotely sensed) to empower community members to more equitably participate in natural climate solutions that can enhance the collective resilience of human and natural populations as global change accelerates. For example, monitoring the state of forest carbon stocks and fluxes is critical to informing climate-smart initiatives at both the entity and national scales. A vital opportunity exists to synthesize current data streams with key additional surveys and/or remotely sensed products into geospatial forest carbon decision-support tools and data clearinghouses.

In addition to underpinning private carbon markets with credible information, the implementation of current and pending domestic and international climate-smart policies raises the need to leverage past foundational work (e.g., FIA plotwork, NASA's Global Ecosystem Dynamics Investigation (GEDI) mission, and other relevant remote-sensing data sets) with emerging technologies/surveys (e.g., machine learning) to meet MMRV needs for national-level reporting as well as the needs of several recent initiatives, including: mature/old-growth risk/opportunity assessments (as mandated by EO14072); European Union Deforestation-Free Supply Chain benchmarking and traceability efforts; CEQ NEPA revisions focused on GHG monitoring; tracking the GHG benefits of activities funded through the Inflation Reduction Act (IRA) such as urban tree planting; and estimating benefits of activities funded through the Bipartisan Infrastructure Law (BIL) such as wildfire reduction.

Key opportunities include increased forest soil sampling aligned with USDA soil carbon inventories, increased urban forest inventories, operational small-area estimation techniques that leverage remotely sensed data (e.g., USGS LANDSAT and NASA NISAR, LiDAR platforms, as well as private-sector and international satellite data), improved stand simulation models to assess GHG effects of climate-smart forest management practices (e.g., FVS), refined accounting

linkages with forest product life cycle assessments and associated long-term carbon implications (e.g., USDA Forest Service Forest Products Lab and Timber Product Output industrial surveys/cooperation), and fuller integration with data sources (e.g., USDA NRCS National Resources Inventory).

6. Improved tracking and reporting of GHG emissions from wildfire and prescribed burns

Proposed implementing agencies: USGS, USDA Forest Service

Subsectors addressed: Forest, grassland

Emissions from wildfires and prescribed burns, including grassland fires, are a major component of national GHG fluxes, yet national GHG inventories and other reporting efforts are not easily comparable as different systems of GHG tracking of wildfires and prescribed burns exist that provide estimates for different fire types, spatial and temporal resolutions, and GHG types. This pilot will deliver an easy-to-use dashboard that is built on existing systems but uses national Landsat data. The dashboard will show estimated GHG gases from wildfires from the 1980s to today, with regular updates. Methods to estimate GHG gases from prescribed fires are currently being developed; these estimates will be incorporated into the dashboard as well once methods are finalized.

7. Forest biomass estimation and mapping

Proposed implementing agencies: NASA, USDA Forest Service

Subsectors addressed: Forest

Algorithms that combine LiDAR, radar, multi-spectral imagery, and other space- and aircraft-based measurements of forests, together with ground-based measurements from (for instance) FIA, can provide unbiased estimates of forest biomass with fine spatial granularity across large spatial extents. This capability has been demonstrated by university, private-sector, and NGO researchers for U.S. and global domains.

LiDAR is a proven technology for directly and accurately measuring forest attributes such as height and cover; attributes that are critical for estimating forest biomass. To date, most forest LiDAR mapping has been achieved with airborne LiDAR sensors, albeit across relatively small spatial extents. However, more recently, spaceborne LiDAR missions, such as ICESat-1, demonstrated the potential of mapping forest biomass at global scales. NASA's GEDI mission is the first spaceborne LiDAR specifically designed to measure vegetation and forest biomass. Since its launch in 2018, GEDI has revolutionized the mapping of forest biomass at local, regional, and global scales, and it now enables the most globally comprehensive and consistent estimates of forest carbon available.

The GEDI mission was originally scheduled to end in 2023, however, NASA has extended the mission. Due to space constraints on the ISS, GEDI was temporarily removed from its operational site in March 2023 and was placed in storage where it will remain for a period of 13 to 18 months. The ISS is planning to reinstall GEDI sometime between April and September 2024 at which point GEDI will resume measurements through the scheduled life of the ISS (~2030). The eventual end of the GEDI mission will lead to a gap in forest biomass estimation capabilities. Agencies will explore potential options for future LiDAR measurements for forest

measurement and biomass estimation, which could include some combination of relying on future satellite missions and airborne LiDAR mapping campaigns.

8. Improved mapping of land conditions in support of national GHG MMRV

Proposed implementing agencies: USGS, NASA, NOAA, USDA

Subsectors addressed: Cropland, grassland, forest

Landsat-based land use and land cover (LULC) data, such as the National Land Cover Database (NLCD), are traditionally used in the U.S. GHG Inventory to represent the 6 primary land use categories and 30 land use conversion categories. The NLCD data are delivered every 2 to 5 years by USGS, in collaboration with NASA, NOAA, and USDA. USGS will work to enhance data structure, frequency, quality, and timeliness of the NLCD data to improve the timeliness and accuracy of the U.S. GHG Inventory and other products that rely on NLCD. In particular, USGS will work to integrate the NLCD with the Land Change Monitoring, Assessment, and Projection (LCMAP) data, which are produced annually and offer a suite of 10 land change and cover products going back to 1985. Integration of the LCMAP and NLCD data will drastically improve the overall quality of the LULC data by (1) increasing the accuracy of the LULC mapping by at least 5 percent as measured by independent data points; (2) processing data collected by early generations of Landsat data in 1970s and early 1980s for LULC mapping purposes; (3) improving the delivery of the LULC data from the current 2- to 5-year interval to a seasonal and annual time interval; (4) innovating and delivering special LULC data on urban centers for GHG tracking purposes; (5) linking with other land surface monitoring products such as drought, water use, fire, rangeland condition, and invasive grass mapping; and (6) providing historical hindcasting, short-term forecasts, and long-term projections based on climate and land use scenarios.

While improvement efforts initially will focus on the U.S. GHG Inventory, they will be beneficial to broader inventory efforts, as many local and regional entities and corporations base their GHG accounting efforts on methodologies, activity data, and emission factors developed as part of the annual U.S. GHG Inventory process.

9. Accelerate adoption of applications and tools that support climate-smart agriculture and forestry

Proposed implementing agencies: NASA, USDA

Subsectors addressed: Cropland, grassland, livestock, forest

USDA will work with NASA to fully leverage NASA's Carbon Monitoring System (CMS), Applied Research program, and field campaigns to support climate-smart agriculture and forestry.

NASA will transition the CMS to enhanced operational readiness for policy- and decision-makers for climate-smart agriculture and forestry across the entity to national scales. The CMS program has made significant inroads in prototyping a variety of solutions to carbon monitoring and assessment at the entity, regional, State, and national scales. The program is now ready for a systemic approach to replicating, transferring, and scaling these solutions. The enhanced program will continue to improve component models and understanding of carbon emissions/uptake while also building networks with interagency, intergovernmental, and private

sector partners to facilitate co-production and use of applications-ready research. The enhanced CMS will maintain and enhance project-level decision-maker partnerships and prototype new applications in response to emerging needs, while also creating program-wide collaborative networks to accelerate the use of research results for climate-smart agriculture and forestry.

The NASA Agriculture Applied Research program is identifying stakeholders, partners, and capabilities to address Earth observations to support climate-smart agriculture policies and practices. The NASA Harvest consortium (focusing on international agriculture) and the NASA ROSES consortium (focusing on domestic agriculture) will identify, develop, and transition Earth observation research for the agriculture community, which includes a growing climate-smart agriculture sector.

NASA has a long history of executing field campaigns to intensively study regions and phenomena of interest (e.g., the Arctic Boreal Vulnerability Experiment (ABoVE), Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ), etc.). NASA will explore opportunities to leverage airborne assets, satellite data, ground measurements, and models to support and enhance climate-smart agricultural management practices.

VII. Conclusion

The strategic priorities and proposed activities outlined in this strategy will enable agencies to build upon current capabilities, leverage existing and upcoming Federal funds, and partner with non-Federal entities to improve the various framework elements of MMRV of GHGs in the agriculture and forest sectors. By making strategic investments in improving science and research, data and data products, models and tools, and monitoring, the U.S. Government can improve the accuracy and reduce uncertainties in its estimates of GHG emissions and sinks from the agriculture and forest sectors. In turn, improved estimates will enable better reporting, analysis and projects related to GHG sources and sinks in the agriculture and forest sectors and ultimately facilitate planning, management and tracking of mitigation opportunities and activities, and enable better outcomes.

List of Acronyms

ABoVE Arctic Boreal Vulnerability Experiment
AFOLU agriculture, forestry, and other land use
ARMS Agricultural Resources Management Survey
ARPA-E Advanced Research Projects Agency-Energy program
ARS USDA Agricultural Research Service
BIL Bipartisan Infrastructure Law
CBI confidential business information
CEAP Conservation Effects Assessment Program
CEFM Cattle Enteric Fermentation Model
CH_4 methane
CMS Carbon Monitoring System
CO_2 carbon dioxide
Crop-CASMA Crop Condition and Soil Moisture Analytics
CRP Conservation Reserve Program
DOE Department of Energy
EO Earth observation
EPA U.S. Environmental Protection Agency
FIA Forest Inventory and Analysis
FIREX-AQ Fire Influence on Regional to Global Environments and Air Quality
FVS Forest Vegetation Simulator
GEDI Global Ecosystem Dynamics Investigation mission
GEOGLAM Global Agricultural Modeling program
GHG greenhouse gas
IPCC Intergovernmental Panel on Climate Change
IRA Inflation Reduction Act
ISS International Space Station
IWG Interagency Working Group
LCMAP Land Change Monitoring, Assessment, and Projection
LULC land use land cover
LULUCF land-use, land-use change and forestry
MMRV measurement, monitoring, reporting and verification

NAHMS National Animal Health Monitoring System

NASA National Aeronautics and Space Administration

NDC nationally determined contribution

NLCD National Land Cover Database

N_2O nitrous oxide

NOAA National Oceanic and Atmospheric Administration

NRCS USDA Natural Resources Conservation Service

NRI National Resources Inventory

PII personally identifiable information

RaCA Rapid Carbon Assessment

SAE small area estimation

UNFCCC United Nations Framework Convention on Climate Change

USDA U.S. Department of Agriculture

USGS U.S. Geological Survey

VegScape Vegetation Condition Explorer