Appendix H. Methods for Energy Independence and Security Act Measuring and Monitoring Requirements

The Energy Independence and Security Act (EISA) (U.S. Congress, 2007) prescribes that the national assessment methodology include a comprehensive strategy for "measuring, monitoring, and quantifying covered greenhouse gas emissions and reductions" from ecosystems—a monitoring plan. Appropriately, the EISA also indicates that the assessment methodology should be used to carry out this mandate. In the context of the EISA and the methodology, therefore, monitoring has two distinct functions. The first is to comprehensively monitor changes in carbon sequestration in and greenhouse-gas (GHG) flux from ecosystems on a national scale. Monitoring at the national scale involves spatial and temporal extrapolation of data collected at specific locations over broad areas using complex biogeochemical models. The second function of monitoring is more classical: measuring change with time at specific locations. This type of monitoring is used to develop and validate the models used for extrapolation.

H.1. Monitoring Objectives and Scope

To fulfill the EISA requirement for monitoring, the principal objectives and their respective scopes are as listed below:

- Provide ongoing, systematic quantification of carbon stocks, sequestration, GHG emissions, and related ecosystem properties and processes in the United States for the purpose of evaluating their status and trends.
- Aggregate and update observational monitoring data for the purpose of validation; for example, assessing the accuracy of model results.
- Provide a basis for evaluating the effectiveness of applied mitigation activities and strategies undertaken to reduce GHG emissions from ecosystems and promote carbon sequestration.

It is intended that the monitoring plan for the national assessment be adaptive to changing data resources, improved methodologies, and evolving requirements for data and information, while maintaining consistency, scientific credibility, and transparency. The monitoring plan also is designed to be closely coordinated with the science-implementation strategy of the North American Carbon Program's (Denning, 2005) other U.S. carbon-cycle research activities.

H.2. Definitions

It is useful to clearly define and differentiate among the three closely related tasks of measuring, quantifying, and monitoring that are prescribed in the EISA. Measurement is defined here as the application of effective tools and techniques for collecting primary data that address data requirements of the national assessment. Two types of measurements are recognized: direct observations (for example, flux towers) and remotely sensed observations (for example, Landsat).

Quantification is defined here as the determination of numerical values for the data products addressed in the national assessment, including current and projected carbon stocks, carbon sequestration, GHG emissions, and reductions in those emissions because of mitigation actions. Quantification in the national assessment is achieved primarily through the spatial aggregation of measurements and model results described in the preceding sections.

Monitoring is defined here as periodic measurement, which enables quantification and validation of GHG fluxes, carbon sequestration, and related ecosystem properties and processes. Another purpose of monitoring is for evaluating the effectiveness of applied mitigation strategies or management actions for increasing carbon sequestration, reducing GHG emission, and related goals.

H.3. Types of Resource Monitoring

Successful large-scale monitoring programs typically incorporate data collected at several spatiotemporal scales, each providing a unique and valuable contribution to the monitoring effort (fig. H1). Plot- and local-scale research and monitoring provide detailed information not observable at larger scales. Long-term monitoring provides trends information not observable by other means. Spatially extensive surveys provide a means to assess variability across ecosystems and provide estimates of population parameters for regions of interest. Remotely sensed data permit observation and assessment at regional to global scales. These data must be synthe-

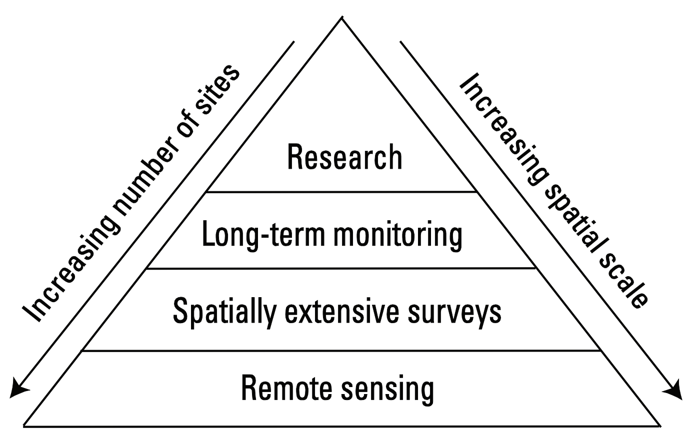

Figure H1. Diagram illustrating types of monitoring needed for assessing carbon sequestration and greenhouse-gas fluxes.

sized into a form that permits quantification over the spatial extent of the monitored area and analysis of change with time.

Although these four types of monitoring represent different spatial scales, they practically and logistically overlap. At the plot and local scale, intensive data collection provides information that is essential for developing a better understanding of carbon-cycling processes. This understanding enables the continued improvement of ecosystem models used to calculate carbon sequestration and GHG fluxes.

Long-term monitoring performed at fixed, georeferenced locations is needed to assess temporal trends in direct measurements of GHG flux and carbon sequestration, as well as to quantify important variables used in flux calculations, such as streamflow, water quality, soil chemistry, and biomass. These types of data provide the ability to assess and distinguish among short-term, seasonal, annual, interannual, and long-term trends. Some examples of programs that could provide key data for the national assessment include the U.S. Geological Survey's (USGS) streamflow and water-quality monitoring programs, the National Oceanic and Atmospheric Administration (NOAA) climate-monitoring program, and the U.S. Forest Service's (USFS) Forest Inventory and Analysis (FIA) Program; additional examples of datasets and programs that could provide data for the assessment are listed in the individual appendixes of this report.

Spatially extensive surveys provide data at regional to national scales that can be used to evaluate how variables change in response to natural or human-related stressors. A key benefit of spatially extensive surveys is that the data can be merged with spatially continuous national land-use and land-cover data, and statistical relations can be developed that permit model estimates of GHG fluxes at sites not directly measured. Surveys of dissolved and particulate carbon in rivers from headwaters to oceans, for example, can be used to examine how concentrations and fluxes of carbon vary in relation to basin size, elevation, land cover, soil properties, and geology. Multiple-regression models then can be created to estimate carbon concentrations and fluxes at unsampled sites. Survey data also can be used to evaluate GHG sources and carbon sinks; spatial patterns in GHG concentrations in the atmosphere and oceans, for example, can be used to identify site characteristics that are useful for flux or carbon sequestration.

Data collected through remote sensing are essential for regional efforts such as mapping and tracking changes in land cover and land use, assessing biomass, and evaluating ecosystem disturbances caused by storms, insects, or fire. For example, multispectral estimating data from the Landsat satellite program are used by the USGS and the U.S. Department of Agriculture (USDA) to create maps of land cover and land use, such the National Land Cover Database (NLCD); these data are updated periodically and are key inputs to modeling changes in carbon storage and GHG flux with time.

H.4. Existing Monitoring Data Sources

The bulk of the data needed to comprehensively monitor carbon sequestration and GHG fluxes are available from existing programs and efforts (U.S. Environmental Protection Agency (EPA), 2010). Monitoring data currently are collected by a wide variety of Federal agencies, including the USGS, NOAA, the National Aeronautics and Space Administration (NASA), the USDA, and the EPA, as well as State and local governments and academic and private monitoring and research efforts. Monitoring data produced by others and needed by the national assessment are derived from a broad range of disciplines, including climate, hydrology, biology, and soil science (table H1). The methods described in other appendixes to this report describe in detail the diverse datasets

Table H1. Example monitoring needs with key parameters and primary areas of application in the assessment.

[Abbreviations and acronyms are as follows: GHG, greenhouse gas; CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; LULC, land cover and land use; LAI, leaf area index; DOC, dissolved organic carbon; POC, particulate organic carbon; DIC, dissolved inorganic carbon]

Monitoring categories (examples)	Key parameters	Primary application
Climate	Precipitation, air temperature, radiation, wind speed	Estimate GHG gas flux and aquatic flux quantification.
GHG fluxes	CO_2, CH_4, N_2O	Direct GHG flux quantification and validation.
Land cover and land use	Percentage change in LULC classes	Estimate carbon inventory.
Disturbances	Fire, insect and disease, storms	Estimate carbon inventory and GHG flux quantification.
Vegetation properties	Biomass, LAI, fuels	Carbon inventory.
Soil properties	Organic and inorganic carbon, soil moisture, permafrost	Carbon inventory and GHG flux quantification.
Water quality	Sediment, nutrients, DOC, POC, DIC	Aquatic GHG fluxes.
Hydrology	Streamflow, groundwater levels	GHG fluxes from terrestrial and aquatic systems.
Coastal primary production	Chlorophyll	Carbon burial in coastal systems.
Ecosystem services	Timber production, habitat condition	Ecosystem impacts.

needed for a national assessment, as well as their identification, assimilation, and evaluation.

There is a strong need for coordination among the existing monitoring programs and data aggregation efforts to support the needs of the national assessment while avoiding a duplication of efforts. Several efforts are proposed or under way to aggregate some of the many types of data needed for regional- and national-scale monitoring into a consistent format, and to make it available for general use, including the science-implementation strategy developed for the North American Carbon Carbon Program (Denning, 2005) . In the absence of a robust and comprehensive data aggregation program housed within another Federal program, this role should be incorporated into the national assessment.

Further, it is suggested that the national assessment evaluate new and existing data sources and data aggregation programs for incorporation into the framework in conjunction with each monitoring cycle. This periodic evaluation would ensure that redundant data-collection and data-aggregation efforts are avoided in fulfilling the EISA requirement for monitoring. It also will ensure that all appropriate available data are assimilated, regardless of source.

H.5. Major Monitoring Needs

H.5.1. Land Use and Land Cover

Land use and land cover (LULC) continually evolves in response to changes in biophysical and socioeconomic driving forces. Providing updated LULC information through an active and sound LULC monitoring system would allow the evaluation of the effects of a changing landscape on carbon sequestration and GHG fluxes.

Land-use monitoring will focus on updating current (2000–2010) LULC information from the perspective of LULC and land management, using updated data on LULC, socioeconomic drivers, and climate to inform and revise scenarios used in periodically updated LULC forecasts and to provide updated 50-year LULC scenario-based forecasts.

The monitoring protocol will leverage existing USGS and agency LULC initiatives, relying on the Multi-Resolution Land Characteristics Consortium (MRLC), specifically, the NLCD and the proposed MRLC monitoring program (Yang, 2008). The goal of the MRLC monitoring strategy is continual updating and augmentation of a multitemporal (annual to 5-year) and multispatial resolution (1 to 250 meters) NLCD to support national-scale environmental and land-monitoring needs. This information, along with updated socioeconomic trends and climate data, will be used to update potential future scenarios and forecasting LULC.

The task of monitoring carbon sequestration and GHG fluxes from vegetated surfaces can be achieved by using a combination of remote sensing and georeferenced plot data. Relative to other ecosystems, forests have far more extensive data-monitoring programs that are suitable for evaluating carbon sequestration and GHG fluxes. The USFS's FIA Program provides a rich database; new programs tasked with improving flux-tower networks and the characterization of vegetation structure, composition, and biomass are critically needed for urban forests, rangelands, and other nonforested systems, which occupy nearly 325 million hectares in the United States. The National Resources Inventory (NRI), administered by the Natural Resources Conservation Service (NRCS), collects such information, but the resulting data have been practically inaccessible; however, they could represent a valuable asset to the monitoring endeavor. Some systems, such as the USDA's GRACEnet ("greenhouse gas reduction through agricultural carbon enhancement" network) and the American flux network (Ameriflux), offer significant promise for monitoring nonforest landscapes and calibrating biogeochemical models, yet they are hardly extensive enough to provide estimates of carbon-sequestration estimates independently for entire landscapes. Likewise, a paucity of data exists describing belowground carbon dynamics, and this deficiency is a clear impediment to reliable estimates of belowground carbon sequestration through time. A more extensive network focused on belowground carbon dynamics is critical. In addition to field-based networks, more remote-sensing data suitable for characterizing vegetation attributes in nonforest landscapes are needed. Some high-resolution LIDAR sensors are available, which will undoubtedly be used to monitor vegetation conditions such as biomass and carbon stocks. The success of the monitoring of vegetated surfaces depends upon leveraging existing networks while developing new data-collection programs, especially in areas lacking sufficient data or exhibiting uncertainty.

Much of the existing knowledge regarding carbon dynamics on vegetated surfaces, especially in nonforested landscapes, describes carbon flux but not sequestration. Thus, long-term studies focused on carbon sequestration, especially soil organic carbon, are needed. More fundamentally, basic research is needed to enable determination of carbon stocks in shrublands. Tens of millions of hectares of these lands exist in the United States alone and have not yet been sufficiently studied in this capacity. To this end, simple equations linking stand structure and cover to standing biomass (and thus standing carbon), which are suitable for regionally scaling standing carbon estimates when coupled with remote-sensing data (such as LIDAR for stand structure), need to be reformulated. Additionally, relatively simple variables, such as aboveground biomass, remain largely uncharacterized in a regional, operational manner. Finally, interagency data sharing is critical for determining other data gaps. Comprehensive evaluation of data sources and their temporal and spatial coverage and suitability for evaluating GHG and carbon-sequestration dynamics is needed to determine true gaps in data.

H.5.2. Soil Carbon Stocks and Fluxes

It is suggested that the assessment will include the quantification of soil carbon stocks and fluxes from organic sources (for example, soil organic carbon (SOC), whereas only stock estimates will be provided from inorganic soil carbon (SIC) pools). Relative to other pools, soil-carbon observations are spatially and temporally sparse. SOC-flux estimates for grasslands and agricultural systems can be obtained from efforts such as those by Ogle and others (2007), which provides quantification of SOC in support of the EPA's official GHG estimates (U.S. Environmental Protection Agency, 2010). Additionally, the GRACEnet program (Jawson and others, 2005) offers a limited number of soil-carbon measurements in primarily agricultural landscapes. In the forest sector, the FIA program provides the most comprehensive forest soil-carbon-monitoring database available (O'Neill and others, 2005). Agency programs and those at research institutions provide a suitable starting point for assimilating and aggregating SOC measures for monitoring purposes. Despite the paucity of programs offering measures of organic carbon components, those aimed at measuring inorganic components are even less numerous. Globally, SIC storage in arid and semiarid soils is approximately 2 to 10 times larger than SOC storage (Schlesinger, 1982; Eswaran and others, 2000). Annual fluxes from inorganic sources, however, are at least an order of magnitude smaller (U.S. Climate Change Science Program, 2007) than fluxes from organic sources. In addition, estimating fluxes from SIC are more difficult than estimating fluxes from SOC (Emmerich, 2003; Svejcar and others, 2008). Therefore, although SIC stocks will be estimated by using the Soil Survey Geographic Database of the NRCS (SSURGO) and the State Soil Geographic Database of the NRCS (STATSGO; replaced in 2006 by the U.S. General Soil Map (STATSGO2)), no estimates of annual flux from SIC will be considered.

Data describing belowground nutrient cycling and carbon sequestration are sparse. More scientific studies aimed at evaluating biophysical processes occurring in soils are necessary to produce more reliable estimates of GHG flux for the United States. To this end, Follett and others (2010) identified the need for a national soil-carbon measurement and modeling network. Such a system would improve the understanding of soil processes and enable better GHG and carbon-sequestration estimates. In addition, more data are needed that describe the annual flux of carbon from inorganic sources, particularly in arid regions where little is known about the primary drivers and magnitude of this phenomenon.

H.5.3. Aquatic Data

Monitoring the aquatic processes related to GHG emission and carbon sequestration presents a set of unique challenges. Inland waters store and transport considerable carbon; thus, quantification of inland processes is critical to the understanding of carbon and GHG processes (U.S. Climate Change Science Program, 2007). Rivers in the conterminous United States export an estimated 30 to 40 million metric tons of carbon per year to the oceans in the form of dissolved and particulate organic carbon and inorganic carbon derived from the atmosphere (Pacala and others, 2001). The fate and magnitude of riverine carbon exported to the coast are critical to accurately quantifying regional and national carbon sequestration (Liu and others, 2000; U.S. Climate Change Science Program, 2007). GHG fluxes also may be significant in estuaries and in the coastal ocean (Blair and others, 2004; Dagg and others, 2004; Punshon and Moore, 2004; Biswas and others, 2007). Given the importance in carbon-sequestration processes and GHG production, it is vital to accurately monitor the fluxes and alterations of carbon and GHG in aquatic systems. It is envisioned that the national assessment will use data primarily from existing USGS streamgaging networks and water-quality programs for monitoring in the terrestrial domain (Seitzinger and Mayorga, 2008) and existing NOAA productivity-monitoring efforts for monitoring in the coastal oceans.

To reduce the uncertainty in modeling carbon fluxes to lakes, impoundments, estuaries, and coastal zones, it is essential to continue and expand existing hydrologic monitoring of the Nation's rivers (streamflow and water quality). Sites should include a continuum from headwaters to the ocean, and better temporal coverage is needed for a range of hydrologic conditions. A large fraction of carbon transport occurs during short, intense events, many of which are driven by storms; thus, a combination of automated samplers and continuous, in-stream monitors are required to obtain improved flux estimates. A comprehensive set of constituents should be measured, including carbon, nitrogen, and phosphorus in all their major forms, as well as turbidity, suspended sediment, chlorophyll, temperature, and conductance. These data should be collected at a sufficient number of sites to allow regression model development within the USGS's "spatially referenced regression on watershed" (SPARROW) and Load Estimator (LOADEST) modeling frameworks; this approach will provide the best available estimates of carbon and nutrient fluxes in rivers and to estuaries.

Despite the importance of GHG fluxes from lakes and impoundments in global carbon and GHG budgets, measurements are sparse and uncoordinated, and there is no centralized database. Methane emissions from the outlets of reservoirs may be particularly important, but they cannot be quantified at regional or national scales with currently available (2010) information. A monitoring program is needed to estimate regional and national GHG fluxes from the surfaces of lakes and impoundments and from the outlets of reservoirs.

Estimates of carbon burial in lakes and impoundments have uncertainty because of the sparseness of sedimentation-rate and carbon-content data used to parameterize statistical models. Existing reservoir-monitoring programs should be expanded to include lakes and small farm ponds.

H.5.4. Priorities for New Data Collection

The national assessment will rely on existing interagency programs for input data for the models that will be used to predict changes in carbon storage and GHG fluxes; however, the accuracy of some model predictions will be limited by sparse (or in some cases, nonexistent) datasets that are needed to parameterize model equations. New data-collection programs are needed to accurately quantify GHG fluxes and sequestration in various ecosystems, especially in nonforest and nonagricultural, terrestrial environments and aquatic habitats. The most critical data gaps in the availability of monitoring data are described in table H2. It is envisioned that the national assessment will coordinate with existing programs to ensure that these gaps are filled. It should be noted that two types of gaps are identified: gaps where ongoing monitoring is necessary to adequately constrain and calculate fluxes that will likely change under future climate regimes, and gaps where data should be collected for a limited time because insufficient data exist to accurately predict fluxes using parameters collected in current (2010) monitoring programs.

Table H2. Critical data gaps in the monitoring effort and recommended solutions.

[Abbreviations and acronyms are as follows: DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; NO_3, nitrate; DON, dissolved organic nitrogen; USGS, U.S. Geological Survey; SPARROW, "spatially referenced regression on watershed attributes" model; GHG, greenhouse gas; CH_4, methane; N_2O, nitrous oxide; FLUXNET, flux network; m, meter; LIDAR, light detection and ranging]

Monitoring target	Data gap and possible solutions
Continuous DOC, DIC, NO_3, DON, chlorophyll, suspended sediment concentrations	New sensors can be used to monitor these constituents' concentrations inexpensively (Downing and others, 2008; Saraceno and others, 2009). Existing data are exclusively from discrete sampling. Recommend installation at key locations, and paired at the river inflow and estuary mouth.
Temperature, conductivity at USGS surface-water gaging stations	Existing USGS gaging network is largely lacking these data, which are critical for models used to predict dissolved and particulate fluxes of carbon and nutrients in rivers, such as SPARROW.
Small water bodies (primarily farm ponds)	Sparsely available data suggest that GHG exchange between small water bodies and the atmosphere may dominate flux of CH_4 and N_2O from many landscapes. The distribution of small water bodies needs to be mapped at high resolution (less than 5 m), and GHG fluxes need to be measured as a subset of them. This will allow creation of statistical models that can be used to estimate GHG fluxes from small water bodies in a given area.
Carbon-burial rates in lakes and impoundments	There are insufficient data to create accurate statistical models for carbon burial in lakes and impoundments across the Nation. Collection and analysis of dated sediment cores from a small subset of lakes and impoundments would greatly improve national carbon-burial-rate estimates.
Groundwater levels and chemistry	Fluctuations in groundwater levels drive carbon storage and GHG production in soils, and groundwater chemistry can influence nutrient fluxes in surface water and coastal systems. A national program for monitoring groundwater levels and chemistry is needed in order to accurately model GHG fluxes from soils and to estimate nutrient fluxes to surface water and coastal oceans.
GHG flux	Additional flux data are critically needed from a variety of domains, in particular for CH_4 and N_2O. Data are especially needed for impoundments, grasslands, and wetlands nationwide. Existing FLUXNET tower sites should be expanded to include more sites and constituents (for example, CH_4 and N_2O). Airborne programs should be implemented to characterize spatiotemporal variability in point fluxes.
Biomass (aboveground and belowground)	Biomass monitoring should be expanded, especially in nonforested habitats, where long-term monitoring data are sparse. A combination of LIDAR, radar, and multispectral data might be suitable for this need, but additional research is needed to make these processes operational.
Changes in boreal vegetation and soil in Alaska	Because of the rapid rate of change in the Alaskan climate, it is critical to quickly develop an interagency, multidisciplinary monitoring program that would include establishment of long-term monitoring, spatial surveys, and remote-sensing capabilities.
Ecosystem disturbances	New research is needed to enhance national capabilities to detect, map, model, and project defoliation and mortality of forests caused by insect outbreaks and storm damages. A first step toward such national capabilities is a healthy long-term Landsat program, and availability of all Landsat scenes acquired and processed at the highest processing level.

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