Public Review Draft: A Method for Assessing Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes in Ecosystems of the United States Under Present Conditions and Future Scenarios

By Zhiliang Zhu (editor), Brian Bergamaschi, Richard Bernknopf, David Clow, Dennis Dye, Stephen Faulkner, William Forney, Robert Gleason, Todd Hawbaker, Jinxun Liu, Shuguang Liu, Stephen Prisley, Bradley Reed, Matthew Reeves, Matthew Rollins, Benjamin Sleeter, Terry Sohl, Sarah Stackpoole, Stephen Stehman, Robert Striegl, Anne Wein, and Zhiliang Zhu

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Conversion Factors

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square miles (mi^2)
megahectare (Mha)	3,861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg) [metric ton (t)]	1.102	ton, short (2,000 lb)
gigagram (Gg)	1.102×10^3	ton, short (2,000 lb)
teragram (Tg)	1.102×10^6	ton, short (2,000 lb)
petagram (Pg)	1.102×10^9	ton, short (2,000 lb)
	Irradiance	
watts per square meter (W/m^2)	0.09294	watts per square foot (W/ft^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8.

The resolution of pixels in spatial datasets follows the conventions used in the spatial data and modeling communities. The format is "*n*-meter resolution," where *n* is a numerical value for the length. The usage translates into a pixel with a length of *n* on all sides that covers an area of *n* meters × *n* meters.

How Megagrams, Gigagrams, Teragrams, and Petagrams Relate to Metric Tons

1 megagram (Mg)	=	1 million grams (10^6 g)	=	1 metric ton (t)
1 gigagram (Gg)	=	1 billion grams (10^9 g)	=	1,000 metric tons
1 teragram (Tg)	=	1 trillion grams (10^{12} g)	=	1 million metric tons (Mt)
1 petagram (Pg)	=	1 quadrillion grams (10^{15} g)	=	1 billion metric tons (Gt)

Abbreviations, Acronyms, and Chemical Symbols

ADAGE	Applied Dynamic Analysis of the Global Economy
AFOLU	agriculture, forestry, and other land uses
AmeriFlux	American flux network
AR4	IPCC fourth assessment report
AR5	IPCC fifth assessment report
ArcFVS	ArcInfo's Forest Vegetation Simulator
ArcSDE	ArcInfo's Spatial Database Engine
ARMS	Agricultural Resource Management Survey
ARS	USDA Agricultural Research Service
AVHRR	Advanced Very High Resolution Radiometer
BAER	Burned Area Emergency Recovery
BCC–BCM2.0	Bjerknes Centre for Climate Research, Bergen Climate Model 2.0
BGC	biogeochemical
BMPs	best management practices
BPS	biophysical settings
C	carbon
C_{ed}	carbon erosion and deposition
C_s	carbon stock
C_{sr}	carbon sequestration
CASA	Carnegie-Ames-Stanford Approach model
CBI	Conservation Biology Institute
CCSP	U.S. Climate Change Science Program
CEAP	Conservation Effects Assessment Project
CH_4	methane
CLUE	Conversion of Land Use and Its Effects
CMIP3	World Climate Research Programme's Coupled Model Intercomparison Project (phase 3)
CO_2	carbon dioxide
COLE	carbon online estimator
COMET-VR	Voluntary Reporting of Greenhouse Gases-Carbon Management Evaluation Tool
CONUS	conterminous United States
CRP	Conservation Reserve Program
CSIRO–Mk3.0	Australia's Commonwealth Scientific and Industrial Research Organisation Mark 3.0
CSP	Conservation Security Program
CSW	Catalogue Service for Web
DCF	discounted cash flow
DED	duck energy day
DEM	digital elevation model
DIC	dissolved inorganic carbon
DLG	digital line graph
DNDC	denitrification-decomposition model

DOC	dissolved organic carbon
DOI	U.S. Department of the Interior
DON	dissolved organic nitrogen
EAC	equivalent annual cost
EcoServ	ecosystem services model
EDCM	Erosion-Deposition-Carbon Model
EDNA	Elevation Derivatives for National Applications
EF	emission factor
EISA	Energy Independence and Security Act of 2007
EnKF	Ensemble Kalman Filter
EPA	U.S. Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
ER	ecosystem respiration
ERF1	Enhanced River Reach File (USGS)
EROS	USGS Center for Earth Resources Observation and Science
ERS	Economic Research
ESCI	ecosystem services change indicator
FACE	Free-Air CO_2 Enrichment
FARSITE	Fire Area Simulator
FASOM–GHG	Forest and Agriculture Sector Optimization Model with Greenhouse Gases
FCCS	fuel characteristic classification system
FGDC	Federal Geographic Data Committee
FIA	U.S. Forest Service Forest Inventory and Analysis Program
FlamMap	fire behavior mapping and analysis program (USFS)
FLM	fuel loading model
FLUXNET	flux network
FOFEM	First Order Fire Effects Model
FORE–SCE	"forecasting scenarios of land cover change" model
FPA	fire program analysis
FPAR	Fraction of Photosynthetically Active Radiation
FRLPP	Farm and Ranch Lands Protection Program
FSPro	Fire Spread Probability model
FVS	Forest Vegetation Simulator
FWS	U.S. Fish and Wildlife Service
GAP	Gap Analysis Program
GCM	Global Circulation Model
GCP	Global Carbon Project
GDP	Gross Domestic Product
GEMS	General Ensemble Modeling System
GeoEye	commercial Earth-observation satellite
GeoMPI	Geospatial Model Programming Interface
GeoMSI	Geospatial Model Sharing Interface
GHG	greenhouse gases
GIS	geographic information system
GPP	gross primary productivity

GRACEnet	"greenhouse gas reduction through agricultural carbon enhancement" network
GRP	Grassland Reserve Program
GSG	Global Scenario Group
GUI	graphical user interface
GWP	global warming potential
HCO_3^-	bicarbonate
HFRP	Healthy Forests Reserve Program
HR	heterotrophic respiration
HUC	hydrologic unit codes
IBIS	Integrated Biosphere Simulator
IC	inorganic carbon
ID	identifier
IKONOS	Earth-observing satellite
INM–CM3.0	Institute of Numerical Mathematics, Climate Model 3.0
InTec	Integrated Terrestrial Ecosystem model
INT-GTR	Intermountain Research Station-General Technical Report
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
J2EE	Java Platform Enterprise Edition
JERS–1	Japanese Earth Resources Satellite 1
JFD	joint frequency distribution
K	soil erodibility factor
LAI	leaf area index
LANDFIRE	Landscape Fire and Resource Management Planning Tools Project
LANDIS–II	Disturbance and Succession forest landscape model
Landsat	USGS and NASA Satellite Program
LANDSUM	Landscape Succession Model
LCCs	U.S. Fish and Wildlife Service's Landscape Conservation Cooperatives
LIDAR	Light detection and ranging
LOADEST	USGS Load Estimator program
LTER	Long Term Ecological Research Network
LULC	land use and land cover
LULCC	land-use and land-cover change
LULUCF	Land Use, Land-Use Change and Forestry
MCMC	Markov Chain Monte Carlo method
MIROC3	Model for Interdisciplinary Research on Climate 3
MODFLOW	groundwater flow model
MODIS	Moderate Resolution Imaging Spectroradiometer
MRLC	Multi-Resolution Land Characteristics Consortium
MTBS	Monitoring Trends in Burn Severity project (LANDFIRE)
MTT	minimum-travel time
N_2O	nitrous oxide
NADP	National Atmospheric Deposition Program
NARR	North American Regional Reanalysis (NOAA)

NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NASQAN	USGS National Stream Quality Accounting Network
NBP	net biome productivity
NCAS	National Carbon Accounting System
NCDC	National Climatic Data Center (NOAA)
NCEP	National Centers for Environmental Prediction
NCWin	NetCDF program for processing and visualizing NetCDF data
NDVI	Normalized Difference Vegetation Index
NECB	net ecosystem carbon balance
NED	National Elevation Dataset
NEE	net ecosystem exchange
NEON	National Ecological Observatory Network
NEP	net ecosystem production
NetCDF	network Common Data Form
NEWS	Nutrient Export from Watersheds model
NFPORS	National Fire Plan Operations and Reporting System
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NLCD	National Land Cover Database
NLM	Nitrogen Loading Model
NO_3^-	nitrate
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary productivity
NPCDI	National Coastal Pollutant Discharge Inventory
NPDES	National Pollutant Discharge Elimination System
Nr	reactive nitrogen
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory (USDA)
NSDI	National Spatial Data Infrastructure
NSF	National Science Foundation
NWI	National Wetlands Inventory
NWIS	National Water Information System
OC	organic carbon
OGC	Open Geospatial Consortium
OM	organic matter
OSU	Oregon State University
P	phosphorus
PAD–US (CBI)	Protected Areas Database of the United States (maintained by the Conservation Biology Institute of Oregon)
PAO	proportion of area occupied
PDF	probability distribution function
PEST	model-independent parameter estimation application (EPA)
PIC	particulate inorganic carbon
PNV	potential natural vegetation

POC	particulate organic carbon
PPR	Prairie Pothole region
PRISM	parameter-elevation regressions on independent slopes model
PRMS	Precipitation-Runoff Modeling System
PVB	present value of the benefits
PVC	present value of the costs
QC/QA	quality control and quality assurance
r_2	coefficient of determination
RAC	Oracle's Real Application Clusters database
RDBMS	Oracle's Enterprise Edition Relational Database Management System
RCP	representative concentration pathways
REDD	reducing emissions from deforestation and forest degradation
redox	reduction-oxidation
RESIS–II	Reservoir Sedimentation Survey Information System (updated version)
RESSED	Reservoir Sedimentation Database
RPA	U.S. Forest Service Forest and Rangeland Renewable Resources Planning Act of 1974
RSLC	remote sensing of landscape change activities at U.S. Geological Survey
SAR	synthetic aperture radar
SEnKF	Smoothed Ensemble Kalman Filter
SIC	soil inorganic carbon
SOC	soil organic carbon
SOCCR	State of the Carbon Cycle Report
SOM	soil organic matter
SPARROW	"spatially referenced regressions on watershed attributes" water-quality model
SRES	IPCC's Special Report on Emission Scenarios
SRTM	Shuttle Radar Topography Mission
SSURGO	Soil Survey Geographic database (NRCS)
STATSGO2	U.S. General Soil Map (formerly STATSGO)
STORET	EPA's Storage and Retrieval Data Warehouse
SWAT	Soil and Water Assessment Tool (USDA)
TDN	total dissolved nitrogen
TIGER®	Topologically Integrated Geographic Encoding and Referencing system of the U.S. Census Bureau
TM	Landsat Thematic Mapper
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorous
TRIPLEX	monthly time-step model of forest growth and carbon dynamics that integrates three BGC models
TSS	total suspended sediments
UMD	University of Maryland
UMCES	University of Maryland, Center for Environmental Science
UNEP	United Nations Environment Programme

USDA	U.S. Department of Agriculture
USDC	U.S. Department of Commerce
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
USPED	Unit Stream Power Erosion and Deposition
VCT	vegetation change tracker (a product of LANDFIRE)
VDDT	Vegetation Dynamics Development Tool
WHIP	Wildlife Habitats Incentives Program
WRP	Wetland Reserve Program
WUE	water-use efficiency

Energy Independence and Security Act of 2007

SEC. 712. ASSESSMENT OF CARBON SEQUESTRATION AND METHANE AND NITROUS OXIDE EMISSIONS FROM ECOSYSTEMS.

(a) DEFINITIONS.—In this section:

(1) ADAPTATION STRATEGY.—The term "adaptation strategy" means a land use and management strategy that can be used—

(A) to increase the sequestration capabilities of covered greenhouse gases of any ecosystem; or

(B) to reduce the emissions of covered greenhouse gases from any ecosystem.

(2) ASSESSMENT.—The term "assessment" means the national assessment authorized under subsection (b).

(3) COVERED GREENHOUSE GAS.—The term "covered greenhouse gas" means carbon dioxide, nitrous oxide, and methane gas.

(4) ECOSYSTEM.—The term "ecosystem" means any terrestrial, freshwater aquatic, or coastal ecosystem, including an estuary.

(5) NATIVE PLANT SPECIES.—The term "native plant species" means any noninvasive, naturally occurring plant species within an ecosystem.

(6) SECRETARY.—The term "Secretary" means the Secretary of the Interior.

(b) AUTHORIZATION OF ASSESSMENT.—Not later than 2 years after the date on which the final methodology is published under subsection (f)(3)(D), the Secretary shall complete a national assessment of—

(1) the quantity of carbon stored in and released from ecosystems, including from man-caused and natural fires; and

(2) the annual flux of covered greenhouse gases in and out of ecosystems.

(c) COMPONENTS.—In conducting the assessment under subsection (b), the Secretary shall—

(1) determine the processes that control the flux of covered greenhouse gases in and out of each ecosystem;

(2) estimate the potential for increasing carbon sequestration in natural and managed ecosystems through management activities or restoration activities in each ecosystem;

(3) develop near-term and long-term adaptation strategies or mitigation strategies that can be employed—

(A) to enhance the sequestration of carbon in each ecosystem;

(B) to reduce emissions of covered greenhouse gases from ecosystems; and

(C) to adapt to climate change; and

(4) estimate the annual carbon sequestration capacity of ecosystems under a range of policies in support of management activities to optimize sequestration.

(d) USE OF NATIVE PLANT SPECIES.—In developing restoration activities under subsection (c)(2) and management strategies and adaptation strategies under subsection (c)(3), the Secretary shall emphasize the use of native plant species (including mixtures of many native plant species) for sequestering covered greenhouse gas in each ecosystem.

(e) CONSULTATION.—

(1) IN GENERAL.—In conducting the assessment under subsection (b) and developing the methodology under subsection (f), the Secretary shall consult with—

(A) the Secretary of Energy;
(B) the Secretary of Agriculture;
(C) the Administrator of the Environmental Protection Agency;
(D) the Secretary of Commerce, acting through the Under Secretary for Oceans and Atmosphere; and
(E) the heads of other relevant agencies.

(2) OCEAN AND COASTAL ECOSYSTEMS.—In carrying out this section with respect to ocean and coastal ecosystems (including estuaries), the Secretary shall work jointly with the Secretary of Commerce, acting through the Under Secretary for Oceans and Atmosphere.

(f) METHODOLOGY.—

(1) IN GENERAL.—Not later than 1 year after the date of enactment of this Act, the Secretary shall develop a methodology for conducting the assessment.

(2) REQUIREMENTS.—The methodology developed under paragraph (1)—

(A) shall—

(i) determine the method for measuring, monitoring, and quantifying covered greenhouse gas emissions and reductions;

(ii) estimate the total capacity of each ecosystem to sequester carbon; and

(iii) estimate the ability of each ecosystem to reduce emissions of covered greenhouse gases through management practices; and

(B) may employ economic and other systems models, analyses, and estimates, to be developed in consultation with each of the individuals described in subsection (e).

(3) EXTERNAL REVIEW AND PUBLICATION.—On completion of a proposed methodology, the Secretary shall—

(A) publish the proposed methodology;

(B) at least 60 days before the date on which the final methodology is published, solicit comments from—

(i) the public; and

(ii) heads of affected Federal and State agencies;

(C) establish a panel to review the proposed methodology published under subparagraph (A) and any comments received under subparagraph (B), to be composed of members—

(i) with expertise in the matters described in subsections (c) and (d); and

(ii) that are, as appropriate, representatives of Federal agencies, institutions of higher education, nongovernmental organizations, State organizations, industry, and international organizations; and

(D) on completion of the review under subparagraph (C), publish in the Federal Register the revised final methodology.

(g) ESTIMATE; REVIEW.—The Secretary shall—

(1) based on the assessment, prescribe the data, information, and analysis needed to establish a scientifically sound estimate of the carbon sequestration capacity of relevant ecosystems; and

(2) not later than 180 days after the date on which the assessment is completed, submit to the heads of applicable

Federal agencies and the appropriate committees of Congress a report that describes the results of the assessment.

(h) DATA AND REPORT AVAILABILITY.—On completion of the assessment, the Secretary shall incorporate the results of the assessment into a web-accessible database for public use.

(i) AUTHORIZATION.—There is authorized to be appropriated to carry out this section $20,000,000 for the period of fiscal years 2008 through 2012.

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By Zhiliang Zhu[1] (editor), Brian Bergamaschi[2], Richard Bernknopf[3], David Clow[4], Dennis Dye[5], Stephen Faulkner[6], William Forney[3], Robert Gleason[7], Todd Hawbaker[4], Jinxun Liu[8], Shuguang Liu[9], Stephen Prisley[10], Bradley Reed[1], Matthew Reeves[11], Matthew Rollins[9], Benjamin Sleeter[3], Terry Sohl[9], Sarah Stackpoole[4], Stephen Stehman[12], Robert Striegl[13], Anne Wein[1], and Zhiliang Zhu[1]

Executive Summary

This methodology was developed to fulfill a requirement by the Energy Independence and Security Act of 2007 (EISA). The EISA legislation mandates the U.S. Department of the Interior (DOI) to develop a methodology and conduct an assessment of carbon storage, carbon sequestration, and fluxes of three principal greenhouse gases (GHG) for the Nation's ecosystems. The three principal GHG are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Section 712 of this legislation (provided in the front of this report) asks DOI to develop the following:

- A methodology that includes quantifying, measuring, and monitoring carbon sequestration and GHG fluxes using current science and available, suitable national datasets
- A resource assessment of the Nation's ecosystems—terrestrial (forests, croplands, wetlands, and others) and aquatic (freshwater systems, estuaries, coastal waters)—focusing on the evaluation of the following:
  - A range of mitigation activities for a potential increase in carbon-sequestration capacity and reduction of GHG fluxes to inform policy analysis
  - Climate-change effects and other controlling processes (including wildland fires) on carbon and GHG uptake and emissions from ecosystems

The legislation requires that an assessment of carbon storage and GHG fluxes in the Nation's ecosystems be performed, including an evaluation of potential policies for climate-change mitigation. Such an assessment is as complex as it is geographically broad, encompassing high ecological diversity and influenced by many present and future potential consequences of climate change, population change, land-cover change, ecosystem disturbances, and land-management activities. This document defines the scope and methods of the assessment in terms of the ecosystems, pools, assessment units, and scale of applications; and explains the interdisciplinary framework and the individual methods and models used to develop assessment reports.

The concepts of ecosystems, carbon pools, and GHG fluxes used for the assessment follow conventional definitions in use by major national and international assessment or inventory efforts such as the Intergovernmental Panel on Climate Change (IPCC), U.S. Global Change Research Program's State of the Carbon Cycle Report, and the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Inventory Report. Ecosystems defined in the methodology are

[1]U.S. Geological Survey, Reston, Va.

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[12]State University of New York, College of Environmental Science and Forestry, Syracuse, N.Y.

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forests, grassland/shrublands, croplands, wetlands, and aquatic habitats (which include inland impoundments, estuaries, and coastal waters). Terrestrial carbon pools include aboveground and belowground biomass, nonliving woody debris and litter, soil organic matter, and harvested wood. Aquatic pools include dissolved organic and inorganic carbon as well as particulate and sedimentary organic carbon. Across the Nation, the EPA's Level II ecoregions map (which delineates 24 ecoregions for the Nation) is the practical instrument for developing and delivering assessment results. Consequently, the ecoregion is the scale of the assessment because the mitigation scenarios, assessment results, validation, and uncertainty analysis are produced at this scale.

For a given landscape, an ecosystem's capacity to increase carbon stocks and reduce GHG flux can be enhanced through changes in land use and land cover (LULC) (such as converting marginal cropland to forest or wetland) and changes in land management (such as increased use of prescribed burning to manage wildland fires). In order to estimate current ecosystem carbon stocks and GHG fluxes and to understand the potential capacity and effects of mitigation strategies, two time periods are used for the assessment: 2001 through 2010, which is used to establish a current ecosystem GHG baseline and validate models; and 2011 through 2050, which is used to assess future potential conditions.

The method for conducting the assessment of future potential conditions uses IPCC storylines and climate scenarios. A reference and three mitigation scenarios are constructed for each storyline. The reference scenario projects LULC and land-management change in the absence of climate-mitigation policy. Alternative mitigation scenarios apply combinations of LULC changes and management activities to enhance carbon sequestration and reduce GHG emissions. In addition, the assessment also will consider the concept of potential natural vegetation as a scenario. Input from regional experts and stakeholders will be solicited to construct realistic and meaningful scenarios.

The methods used in the assessment include a current (2010) baseline component and a future potential component. The baseline component uses existing inventory and remote-sensing data to measure and analyze spatial and temporal distributions of carbon stocks and GHG fluxes. The future potential component starts with the IPCC scenarios and examines the underlying economic and policy assumptions. The economic and policy assumptions are then translated into spatially and temporally resolved projections of future LULC in annual steps. Projections of future climate under different scenarios are obtained by downscaling data from global climate models. Future potential ecosystem disturbances, such as wildfires, are modeled in a similar manner. Using a geographic information system (GIS), data on the projected climate, LULC, and ecosystem disturbances are integrated to generate georeferenced layers of information that describe the future distribution of ecosystems and vegetation. The product of these analyses is a map of future ecosystems and ecosystem conditions for each future year and each scenario. These annual maps form the basis for calculating carbon storage and GHG emissions.

The carbon storage, carbon-sequestration capacities, and GHG emissions from terrestrial and wetland ecosystems under projected future conditions are assessed quantitatively from these GIS-produced maps using a spatially explicit biogeochemical ensemble modeling system that incorporates properties of management activities (such as tillage or harvesting) and properties of individual ecosystems (such as elevation, vegetation characteristics, and soil attributes) and integrates them with the LULC and climate data. In addition to carbon storage and GHG fluxes, this model also provides important ancillary information about water use and other ecosystem services. Assessment of aquatic habitats also is based on the maps, but uses empirical models. The export of carbon in rivers, the flux of carbon and GHG into or out of inland basins (such as ponds, lakes, and reservoirs), and the impact of modified nutrient and sediment loads on carbon storage and GHG flux into or out of estuarine and coastal waters are assessed for the projected future conditions. Validation and uncertainty analysis of the assessment results follows established technical protocols, such as IPCC guidelines on assessing and reporting uncertainties. The assessment results (for each annual map of projected future ecosystem conditions and associated uncertainties) (1) permit the reporting of probability distributions of effects and the effectiveness of controlling processes and potential mitigation activities, and (2) support an analysis of potential policy applications.

The success of the assessment will depend on the methods and models used and the availability of suitable observational data. A wide variety of datasets for input are needed: carbon and GHG measurements (such as forest inventory or flux-tower data), streamgage data, remote-sensing data (such as precipitation, land-cover maps, and wildfires), soil attributes, current and future projected climates, agriculture and forestry production data, and a host of other input data. In addition, an approach for ecosystem GHG-flux monitoring is outlined in the methodology.

Implementation of the methods and access to datasets requires collaborations among various Federal agencies, State agencies, nongovernmental organizations, and the science community. For example, sharing or developing input data will be critical to the assessment, thereby ensuring a common basis to produce consistent assessment results, which then becomes important when making comparisons to other existing inventory or assessment efforts. Participation by experts or stakeholders in understanding the needs of policymakers and developing realistic mitigation scenarios will lead to improved accuracy in assessment results. Collaborative research on carbon cycling, GHG fluxes, ecosystem services, and model or method comparisons will help improve the methodology and enhance user confidence in assessment results. Applications of the assessment for mitigation planning or creating other land-management policies also will provide opportunities for validating the assessment results and for monitoring future mitigation performances. Not all data and information needs can be met adequately. Further research and development will be needed as described in the document.

Using the method described in this document, the assessment can be completed in approximately three years. The primary deliverables will be assessment reports that present the results in the form of tables, charts, and maps. Changes in carbon stocks, net ecosystem carbon balance, GHG fluxes, and other services in ecoregions will be reported annually for 2001 through 2050 by ecosystem, pool, and scenario. These results will be used to examine policy- or research-relevant questions, such as the following:

- What are estimates of the ecological carbon-sequestration capacity and GHG flux of the Nation's ecosystems under different future climate scenarios, and how do these estimates vary geographically and temporally?
- How effective are management practices, such as no-till agriculture or fire suppression, on short- and long-term carbon sequestration and GHG fluxes?
- How effective are deliberate changes in land use, such as reforestation or wetland restoration, on carbon-sequestration capacity and GHG emissions?
- What might be the most effective and economically feasible regional mitigation strategies?
- How might other ecosystem services, such as water yield or wildlife habitat conditions, be affected by mitigation strategies to enhance carbon sequestration?
- How will changes in the terrestrial supply of carbon, nutrients, and sediments to inland basins, estuaries, and coastal oceans affect carbon sequestration and GHG production, including potential effects on natural processes and mitigation actions such as enhanced algal production and wetland restoration?

In short, the methods described in this document represent a nationally consistent, comprehensive effort to assess carbon storage and GHG fluxes covering the ecosystems of all 50 States. The assessment will rely on the contribution of agencies and scientists for expert evaluation of data, models, and validation, thereby linking to the best available approaches at each phase of the assessment. The results will permit (1) an evaluation of a range of policies and mitigation options, and (2) an evaluation of the effects that changes in demography, LULC, and climate will have on carbon stocks and GHG fluxes in ecosystems.

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1. Introduction

This chapter briefly summarizes DOI's responsibilities and explains the concepts and requirements contained in Section 712 of the Energy Independence and Security Act of 2007 (U.S. Congress, 2007). A firm understanding of these concepts and requirements is necessary because they form the foundation upon which to construct the methodology for carrying out the assessment.

1.1. Requirements of Section 712 of the Energy Independence and Security Act of 2007

In 2007, the U.S. Congress passed Public Law 110–140, the Energy Independence and Security Act (EISA). Section 712 of the EISA (provided in the front of this report; U.S. Congress, 2007) authorizes the U.S. Department of the Interior (DOI) to develop a methodology and conduct an assessment of the Nation's ecosystems for (1) carbon storage and sequestration, and (2) the fluxes of three greenhouse gases (GHG)—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Ecosystems (such as forests, wetlands, croplands, grassland/shrublands, and aquatic habitats) both sequester and emit greenhouse gases and, to certain extent, can be managed in order to increase carbon sequestration or decrease emissions to help mitigate the effects of burning fossil fuels. The EISA also states that a purpose of the assessment is "to promote research on and deploy greenhouse gas capture and storage options."

Section 712 begins with the definition of terms used in the law. Some of these terms, as well as others used in this report, are included in the glossary found at the end of this report. Section 712 also contains specific requirements—mainly that DOI must develop a methodology, complete a national assessment, and report on that assessment; in the process, DOI must use native plant species and consult with other government agencies. Within the sections entitled "Authorization of Assessment," "Components," and "Methodology," the law specifies the information that the methodology and assessment must include.

To understand the requirements of section 712 of the EISA and maintain the usage and intent of the terminology, key concepts in the legislative language are defined below. These concepts and requirements include assessment, ecosystems, mitigation and adaptation strategies, carbon-sequestration capacity, major processes that control greenhouse-gas fluxes, management and restoration activities, range of policies, the use of native plant species, and components of the methodology.

1.2. Understanding the Concepts and Requirements of the Energy Independence and Security Act of 2007

1.2.1. Assessment

The EISA requires an assessment of resources. In this assessment, the resources are the three greenhouse gases covered by the EISA: carbon dioxide, methane, and nitrous oxide. A resource assessment is a measurement or an estimate that determines the amount of a resource. The requirement for an ecosystem-based assessment by the legislation suggests, accordingly, a quantitative evaluation of the ecological processes and ecosystem capacities of carbon sequestration and GHG fluxes. The assessment needs to establish baseline conditions and therefore overlaps with existing resource (such as forest and rangeland) inventories; however, the focus of the assessment is on the estimates of future potential ecosystem capacities for fluxes of the three gases.

1.2.2. Ecosystems

An ecosystem is generally defined as a functional unit of the environment consisting of physical and biological components (Heal and others, 2005). Examples of ecosystems are provided in the EISA in terms of terrestrial systems, freshwater systems, and coastal aquatic systems (including estuaries). This context is consistent with the definitions of the ecosystems that are used in other global and national studies, which are reviewed in chapter 2 of this report; those studies consistently used forests, wetlands, croplands, grassland/shrublands, and aquatic habitats as ecosystems for assessment and reporting purposes. The specific definitions, boundaries, and scale of ecosystems for this assessment are discussed in chapter 3 of this report.

Among the major functions of ecosystems is land cover and land use. Land use is generally defined as the anthropogenic use of land resources, typically in terms of economic decisions for the land. Land use can be referred to in terms of types of land use (such as agricultural or forest land) and management conducted within a type of land use (such as fertilization of agricultural land or controlled burning of forest land). Land cover refers to the actual vegetative or other surface cover at any given time. Land cover is related to land use in that it is often the result of economic land-use decisions. The effects of changes in both land use and land cover often need examination. Given the inextricable relationship between land use and land cover (LULC), changes in LULC often are considered simultaneously.

1.2.3. Adaptation and Mitigation Strategies

The EISA requires the development of "near-term and long-term adaptation strategies and mitigation strategies;" however, the law only defines adaptation strategy, not mitigation strategy. Adaptation strategy is defined as "a land use and management strategy that can be used (A) to increase the sequestration capabilities of covered greenhouse gases of any ecosystem, or (B) to reduce the emissions of covered greenhouse gases from any ecosystem."

This definition, however, is more consistent with the standard definition of mitigation, which is the taking of action to avoid, reduce, minimize, rectify, or compensate for adverse impacts (see National Environmental Policy Act of 1970; U.S. Congress, 1970). In contrast, adaptation refers to changes in natural systems or "actions taken to enhance the resilience of vulnerable systems, thereby reducing damages to human and natural systems from climate change and variability" (Scheraga and Grambsch, 1998, p. 85). Therefore, it is reasonable to consider mitigation strategies as portfolios of land-use change and land-management activities that are implemented over time and across landscapes to enhance carbon sequestration and reduce GHG emissions. Estimation of carbon sequestration and GHG fluxes for various climates scenarios should inform the development of strategies to adapt to climate change.

1.2.4. Carbon-Sequestration Capacity

EISA requires that the assessment shall "estimate the annual carbon sequestration capacity of ecosystems." The term "carbon sequestration" is defined in this methodology as the removal of CO_2 from the atmosphere and its storage in ecological sinks (terrestrial and aquatic ecosystems). Carbon sequestration can be quantified as a change in the amount of carbon stocks either in an ecosystem or between ecosystems. The term "carbon-sequestration capacity" can refer to both the maximum rate of carbon storage (such as the rate of growth measured for an actively managed forest) and the maximum amount of carbon that can be stored (such as in an old-growth forest or a boreal soil pool).

The reporting of annual rates of carbon storage and changes in carbon stocks is questionable given the amount of annual variance in climate and in vegetation productivity. All ecosystems have a finite storage capacity for a given climate that is limited by ecophysiological constraints on primary productivity, respiration, and decomposition, resulting in a net carbon balance (Chapin and others, 2006). The storage capacity for a given landscape or region can be determined by the extent of specific factors or processes, including changes in LULC and changes in land management within the defined area.

1.2.5. Processes That Control the Flux of Covered Greenhouse Gases

The EISA requirement to "determine the processes that control the flux of covered greenhouse gases" is understood as a requirement to determine the effects of the processes rather than to conduct experiments to identify the processes; these processes (such as photosynthesis, respiration and decomposition, LULC, land management, and ecosystem disturbance) are generally well understood and have been extensively documented in the scientific literature. A general review of the processes and their effects is provided in chapter 2. A key controlling process for GHG fluxes in ecosystems is fire caused by natural and human processes, which is generally considered as either a function of ecosystems or a disturbance. The legislation requires that wildland fire be assessed for its effect on carbon storage and releases. The methodology thus will incorporate existing scientific knowledge to quantify the effects of the relevant controlling processes on carbon sequestration and GHG flux.

1.2.6. Management Activities and Restoration Activities

The EISA requires that the assessment shall "estimate the annual carbon sequestration capacity of ecosystems under a range of policies in support of management activities to optimize sequestration." As defined above for mitigation strategies, management and restoration activities are considered components of mitigation strategic portfolios that are developed in order to increase ecological carbon sequestration and (or) reduce GHG emissions. Changes in management or restoration activities occur within a LULC class (for example, reduced tillage on croplands, wildland fuel treatments, rice-paddy management, or controlled water flow in freshwater systems). For the purpose of assessing ecological carbon-sequestration capacity, land-use change and land-management activities are limited to those that directly increase carbon sequestration in soils, vegetation, wood products, and sediments. Not included are (1) the indirect effects on climate mitigation from the generation of energy from biomass; (2) technological actions that can aid in ecologically sequestering carbon but are not explicitly a land-use or management change (for example, growing algae in industrial fluxes); (3) activities to reduce downstream or life-cycle GHG fluxes (for example, GHG emissions from hauling and processing of timber are not assessed even though they are the result of harvest rotation changes); and (4) GHG emissions from livestock. To address these broader implications, it will be necessary to use results of the assessment in other life-cycle analyses, such as the various ongoing efforts that analyze biomass for energy applications.

The consideration of mitigation activities will require information on potential ancillary effects for other ecosystem services because these services may either limit or enhance the implementation of a particular land-use change or management activity, thus changing the potential for increasing carbon sequestration. In addition, losses and gains to ecosystem services can be expressed as (nonmarket) social values (Brookshire and others, 2010; Jenkins and others, 2010). Evaluating indirect or ancillary effects of mitigation strategies on ecosystem services is a necessary and critical part of the assessment and is directly relevant to informing the policy process, particularly because of the environmental impact review requirements by the National Environmental Policy Act of 1970 (U.S. Congress, 1970).

1.2.7. Range of Policies

The EISA requirement "to estimate the annual carbon sequestration capacity of ecosystems under a range of policies in support of management activities to optimize sequestration" is understood as estimating the carbon-sequestration capacity of ecosystems for a range of land-use change and management activities which will in turn inform policy analyses. Policy analyses of management activities and land-use change alone would be suboptimal; the results of this assessment should be considered together with climate-mitigation-policy analyses that include other mitigation options besides ecological carbon sequestration (for example, Creyts and others, 2007) that pertain to other sectors (such as energy) for informing policymaking. These broader analyses accommodate (1) multiple and competing uses of land for carbon sequestration, food, fiber, and energy; (2) interactions between multiple sectors; and (3) international impacts (for example, Lewandrowski and others, 2004; Murray and others, 2005; U.S. Environmental Protection Agency, 2008; Larsen, 2009; Ross and others, 2009). This national assessment can evaluate mitigation activities and strategies for carbon-sequestration capacity and effects on GHG emissions, and ancillary ramifications on cost and ecosystem services, but otherwise needs to link to the other policy analyses, such as the three examples given above.

1.2.8. Use of Native Plant Species

The EISA requires that the assessment should "emphasize the use of native plant species." The assessment requires that the plants will be used in the restoration, management, and mitigation activities. In this methodology, when plant species are evaluated as part of assessing management activities, only native plant species are considered.

1.2.9. Measuring, Monitoring, and Quantifying

The EISA stipulates that the methodology for the national assessment shall include methods for "measuring, monitoring, and quantifying covered greenhouse gases emissions and reductions." In the context of the national assessment, these three closely related activities are defined as follows:

"Measuring" is applying effective tools and techniques for collecting primary data that address information requirements of the national assessment. Measurement can be subsidiary to the quantification task defined below (for example, providing data for input into a model) or independent of it (for example, providing data for validation or monitoring). Measurement products to be used by the national assessment include past (archived), current, and future data records. Measurement products may be provided by ongoing national inventory programs (such as plot-based biomass measurements by the U.S. Forest Service's Forest Inventory and Analysis Program) or by the use of remote-sensing methods (such as fire perimeters defined by using satellite imagery).

"Monitoring" is the continual, systematic repetition of measurement defined above. The objectives of monitoring for this assessment are to enable the following:

- Quantification through time of carbon stocks, carbon sequestration, GHG emissions, and related ecological processes by providing the data required for calibrating, updating, and improving the accuracy of methods and assessment results
- Validation or assessment of the accuracy and precision of assessment results
- Evaluation of the effectiveness of applied LULC changes, management activities, and mitigation strategies for increasing carbon sequestration, reducing GHG emission, and related goals

"Quantification" is the determination of numerical values for variables specified in the national assessment for specific ecosystems, including current and projected future potential carbon sequestration, GHG emissions, and reductions in those emissions due to LULC change and management activities. Quantification in the national assessment is achieved primarily through the methods described in chapter 3.

1.2.10. Use of Economic and Other Systems Models, Analyses, and Estimates

The EISA notes that the methodology may involve the use of "economic and other systems models, analyses, and estimates." In order to select appropriate models, certain factors will be considered, such as (1) a consensus by the scientific community that the model is of a high enough quality, (2) technical practicality or operational considerations, (3) availability of input data to support the particular method, and (4) whether the models can be integrated with each other and produce results that are consistent with other similar ongoing assessment efforts.

1.3. Summary

In summary, the components of the assessment required by section 712 of the EISA represent a progression from science to policy: (1) existing scientific knowledge is incorporated in order to quantify the effects of the relevant controlling processes on carbon sequestration and GHG flux, (2) increased carbon sequestration and reduced GHG emissions in ecosystems from LULC change and land-management activities are estimated, (3) mitigation strategies under a range of climate-change projections are examined, and (4) activities to enhance sequestration capacity are identified and their costs and effects on ecosystem services are examined as contributions to the policymaking process. The methodology criteria require the preparation of data products to support the informational needs of the assessment (measuring); an estimation of the current and projected future potential carbon sequestration, GHG emissions, and reductions in those emissions due to LULC change and management activities (quantifying); and the calibration, validation, and updating of results (monitoring). Consultation with other agencies is integral to the assessment, as are productive partnerships for implementing the methodology.

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2. Review of Concepts and Literature

The intent of this chapter is to summarize current knowledge about the carbon cycle and GHG fluxes in the Nation's ecosystems and associated controlling processes. A review of large-scale (continental or national-scale) inventories and assessments also is provided.

2.1. Major Carbon-Cycle Processes and Pools

Carbon research, covering global to local scales, informs our understanding of the potential role of ecological sequestration in offsetting carbon emissions. Observations and modeling indicate that annual rates of CO_2 accumulation in the atmosphere are far larger than can be balanced by natural ecological processes that remove CO_2 from the atmosphere (U.S. Climate Change Science Program (CCSP), 2007; Le Quéré and others, 2009). Global carbon sinks vary annually, but from 1990 to 2000, on average the land sink accumulated 2.6±0.7 petagrams of carbon per year (PgC/yr) and the ocean sink accumulated 2.2±0.4 PgC/yr . In 2008, the global average uptake rate for land was 4.7±1.2 PgC/yr and for oceans was 2.3±0.4 PgC/yr, but annual CO_2 emissions from fossil-fuel combustion for the same year were estimated to be 8.7 PgC (Global Carbon Project (GCP), 2009; Le Quéré and others, 2009). Therefore, mitigation of net global carbon emissions ultimately will require both a reduction in the sources of CO_2 to the atmosphere as well as maintaining and increasing terrestrial and aquatic sinks (CCSP, 2007).

Although biological and anthropogenic controls over carbon cycling and GHG flux vary among major ecosystems, the basic ecophysiological processes controlling the accumulation and loss of carbon to and from ecosystems are similar. The primary CO_2 fluxes between the atmosphere and ecosystems are uptake through plant photosynthesis and release by respiration, decomposition, and combustion of organic matter (Paustian, Ravindranath, van Amstel, and others, 2006). Carbon fluxes associated with aquatic ecosystems occur through lateral transfer via rivers and streams, sedimentation and burial in inland and coastal waters, and emission of GHGs from water bodies (CCSP, 2007; Tranvik and others, 2009). Both CH_4 and N_2O emissions are largely caused by microbial processes and combustion of organic materials in fires. For example, CH_4 is released through methanogenesis under anaerobic conditions in soils and during incomplete combustion of organic matter, and N_2O is a byproduct of nitrification and denitrification (Faulkner, 2004; Wiedinmyer and Neff, 2007). These GHGs (CO_2, CH_4, and N_2O) have atmospheric consequences and the IPCC developed the global warming potential (GWP) concept to compare their climate impact. The GWP is a measure that combines the effects of the radiative influence of a gas into the atmosphere relative to CO_2 as well as the residence time of the gas in the atmosphere (Ramaswamy and others, 2001). Carbon dioxide is the standard to which other gases are compared, so it has a GWP of 1. Methane has a GWP of 21, and nitrous oxide is the most potent greenhouse gas with a GWP of 310 (U.S. Environmental Protection Agency, 2010).

Terrestrial and aquatic ecosystems play an important role in the carbon cycle (fig. 2.1). Major ecosystems that are

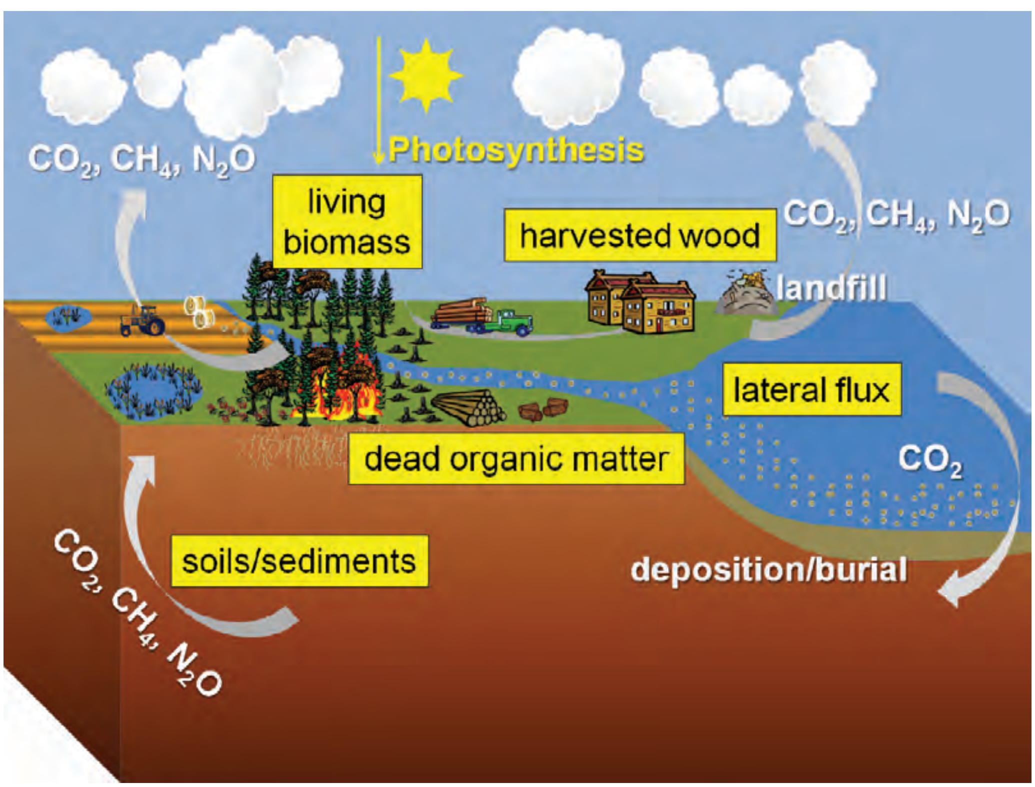


Figure 2.1. Diagram showing primary ecosystem carbon pools. These pools (yellow boxes) include the following: living biomass (above and below the ground), dead wood, litter, soil organic matter, harvested wood, and lateral flux (dissolved organic and inorganic carbon; particulate organic carbon). Abbreviations are as follows: CH_4, methane; CO_2, carbon dioxide, N_2O, nitrous oxide.

commonly considered in both global and national carbon assessments and in inventories include forests, croplands, grassland/shrublands, and wetlands. Carbon cycling in aquatic ecosystems (such as rivers, lakes, and coastal waters) has not received as much attention, particularly in inventories at the national level (Cole and others, 2007; Battin and others, 2009). Plant biomass, both aboveground and belowground, is a main pool of carbon. The amount of carbon stored in plant biomass is influenced by land use. For example, forest clearing for cropland greatly reduces the amount of carbon stored in the vegetative biomass. In a natural system, most of the biomass production contained in living plant material is eventually transferred to dead organic matter pools, such as dead wood and litter. Dead organic matter on the ground and plant biomass below the ground decompose and transform into soil organic matter (SOM), which is another primary pool and can have varying residence times in the soil. Decomposition of SOM releases CO_2 back into the atmosphere (Chapin and others, 2006; Paustian, Ravindranath, van Amstel and others, 2006). Rivers receive dissolved particulate inorganic carbon (PIC), particulate organic carbon (POC), dissolved inorganic carbon (DIC), and dissolved organic carbon (DOC) from terrestrial ecosystems and transport it downstream. A fraction of this carbon is emitted as GHGs during transport and most of the remainder is buried in aquatic sediments in inland basins, waterways, coastal areas, and oceans (Cole and others, 2007; Tranvik and others, 2009).

By assessing carbon fluxes among all major pools, it is possible to summarize all resulting quantities as the net ecosystem carbon balance (NECB) for each ecosystem (Chapin, and others, 2006). This value accounts for net ecosystem production (NEP), which is calculated by subtracting ecosystem respiration (ER) from gross primary productivity (GPP). Net biome productivity (NBP) is based on NEP, but further accounts for ecosystem disturbances. The NECB integrates all carbon flux terms, including lateral runoff and river transport of carbon (Chapin and others, 2006).

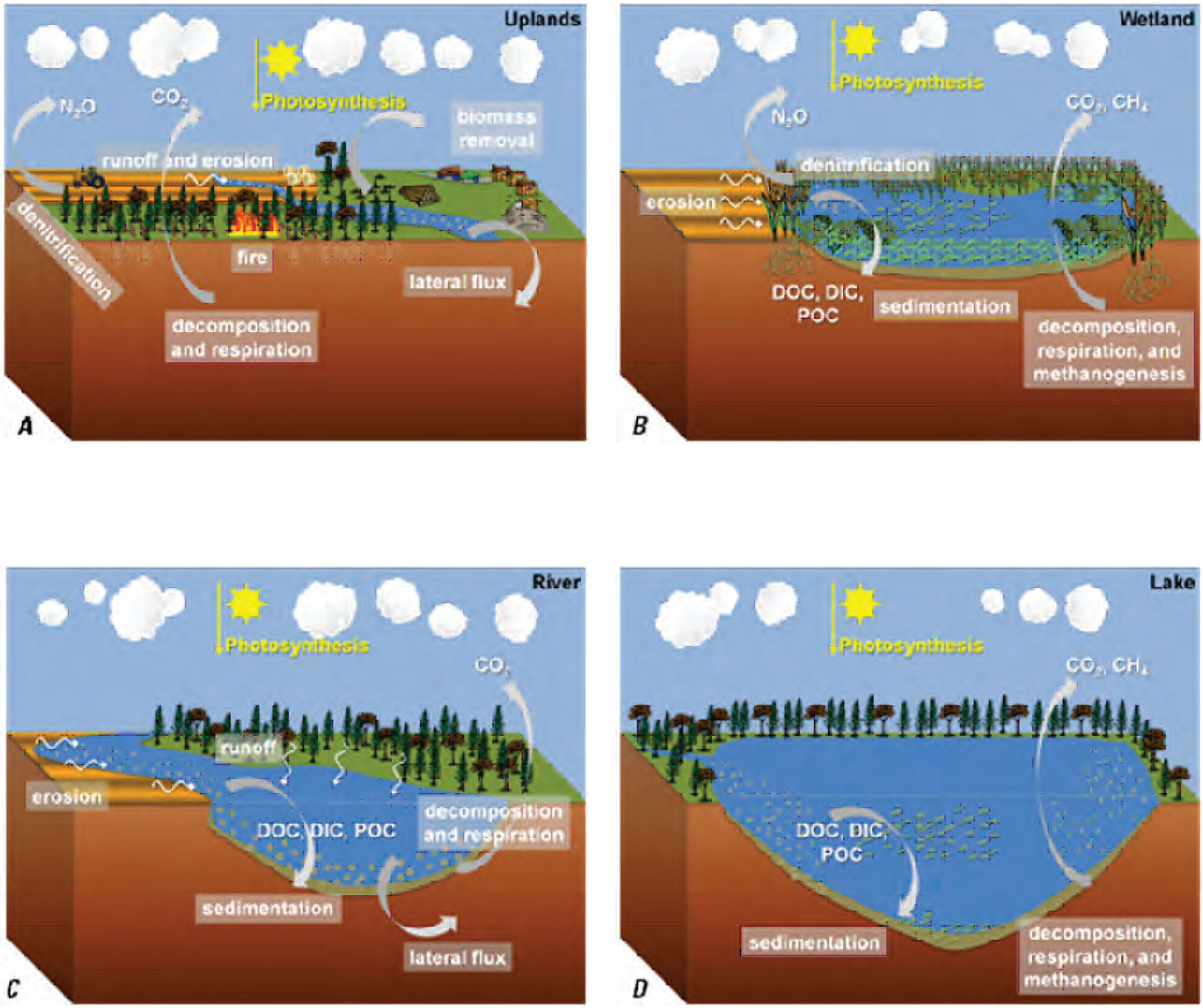
2.2. Current Knowledge of the Carbon Cycle and Greenhouse-Gas Fluxes in the United States

Recent studies indicate that terrestrial ecosystems in the United States represent a sizeable and globally important carbon sink (Potter and others, 2007). Forests are a large carbon sink, but they are ecosystems that gain and lose carbon continually (fig. 2.2*A*). Photosynthesis is the driving process behind carbon storage in biomass, and the stored biomass eventually ends up in soils and dead organic matter pools. Respiration, decomposition, and combustion (fire) release CO_2 and CH_4 back into the atmosphere (see section 2.3.2 for more information on the impacts of ecosystem disturbances on forests). A forest will show a net gain or loss of carbon based on the balance of these processes. One forest may be highly variable in its carbon-storage capacity if it is measured over a long time period, in part because of natural disturbances and harvest events; however, when considering many different forests in a large region, such variability in carbon storage will not be as apparent because the region is composed of forests that are in different stages of recovery and regrowth. In the conterminous United States, forests cover about 246 million hectares, with an additional 52 million hectares in Alaska (Goodale and others, 2002). The forest carbon stock in the conterminous United States is 41 Pg and Alaska has an additional 16 Pg, as estimated by forest inventories (Birdsey and Heath, 1995; Goodale and others, 2002). The forest product pool is a considerable carbon sink that sequesters 57 teragrams of carbon per year (TgC/yr) (CCSP, 2007, also known as the first State of the Carbon Cycle Report, or SOCCR, throughout this report), but individual wood products can have widely varying decomposition rates (Ryan and others, 2010).

Croplands can be very productive ecosystems, and often this productivity is measured in terms of crop yield; however, the accumulation of carbon in plant material is transient, as the plants are mostly herbaceous, and often the plants have an annual life cycle and a constrained growing season. Therefore, the majority of carbon in croplands actually is held in the soil as annual litter additions slowly decompose and become part of the soil organic matter (CCSP, 2007). To some extent, fire plays a role in the combustion of carbon from these lands because farmers sometimes burn plant residues on the soil surface to release nutrients back into the soil. In croplands, N_2O emissions are driven by a combination of factors including fertilization levels, crop type, and soil-drainage capacity (Del Grosso and others, 2005). In the conterminous United States and Alaska, croplands cover about 134 million hectares, and the cropland carbon stock for these regions is about 16 Pg (Bliss, 2003).

Grassland/shrubland ecosystems are similar to croplands in that most of the carbon stock is stored in the soil. Plant roots provide the primary input of carbon into grassland soils, but some of the carbon is oxidized by soil microbes and is released back into the atmosphere. Grassland/shrublands can be net sinks for carbon, although the capacity of these ecosystems to store carbon is variable across the landscape (Reeder and others, 2000). Grasslands/shrublands are subject to woody encroachment, which is the invasion of woody species into grasslands, or of trees into shrublands. In the conterminous United States and Alaska, grasslands/shrublands cover about 345 million hectares, and the grassland/shrubland carbon stock for these regions is about 20 Pg (Bliss, 2003). Many grassland/shrubland ecosystems are used as rangelands or pasturelands in the United States. Rangelands, which are dominant in the Western United States, have native grasses, forbs, or shrubs. Pasturelands, which are more dominant in the eastern part of the United States, contain introduced forage plant species rather than native plants. On rangelands and pasturelands, N_2O emissions are largely influenced by the presence of livestock (Follett and others, 2010).

Wetlands are transitional areas between uplands and aquatic ecosystems and generally can be defined as lands that are inundated periodically or permanently with water, or have



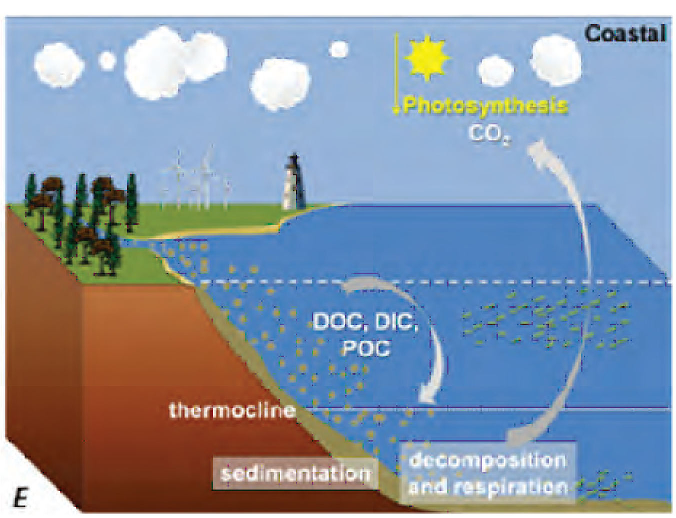


Figure 2.2. Diagrams showing the main carbon and nitrogen cycling processes associated with five major ecosystems in the United States. The main carbon and nitrogen cycling processes associated with these ecosystems are photosynthesis, respiration, decomposition, methanogenesis, denitrification, sedimentation, lateral flux, combustion, and harvesting biomass. *A*, Uplands (includes forests, grassland/shrublands, and croplands). *B*, Wetlands. *C*, River. *D*, Lake. *E*, Coast. Abbreviations are as follows: CH_4, methane; CO_2, carbon dioxide; N_2O, nitrous oxide; DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; POC, particulate organic carbon.

saturated soils, and support vegetation adapted to anaerobic conditions (fig. 2.2*B*). Carbon is stored mainly in the soil carbon pool, which is the result of saturated, anaerobic soils that slow the decomposition of biomass production; however, both woody and nonwoody vegetation and sediments also contribute to sequestered carbon in wetlands. The primary productivity in wetlands can be highly variable; wetlands that receive most of their water from precipitation have low primary productivity, but wetlands (such as river floodplains) that receive pulses of nutrients typically are very productive (Reddy and DeLaune, 2008). Carbon is lost from wetlands through methanogenesis in anaerobic soils and through oxidation of organic matter when wetlands are drained. Therefore, wetland carbon sequestration is a balance of soil and plant carbon sequestration, loss of carbon through methanogenesis, and loss of carbon due to drainage of wetlands. Only 48 percent of the original wetland area in the conterminous United States still exists (CCSP, 2007). The current wetland acreage in the conterminous United States is 70 million hectares with 43 million hectares more in Alaska. Wetlands in the conterminous United States store 20 PgC. An additional 42 PgC are stored in Alaskan wetlands (Bridgham and others, 2006).

Global estimates exist for GHG fluxes from inland waters (Tranvik and others, 2009), and national estimates exist for the export of carbon from rivers to oceans (Pacala and others, 2001); however, national estimates of GHG fluxes from inland waters (for example, lakes and impoundments), coastal systems, and estuarine systems are lacking. Rivers (fig. 2.2*C*) in the conterminous United States export an estimated 30 to 40 TgC/yr to the oceans (Pacala and others, 2001) and global exports have been estimated at 0.9 PgC/yr (Tranvik and others, 2009). Exports are the sum of four carbon fractions: PIC, POC, DIC, and DOC. Globally, approximately 46 percent of riverine carbon is in organic form (25% dissolved and 21% particulate) and 38 percent is transported as dissolved CO_2 (CCSP, 2007).

Considerable amounts of dissolved carbon and sediment are transported and then stored in inland water bodies, estuaries, and coastal waters (fig. 2.2*D*). For example, global estimates state that lakes stored 820 Pg of carbon during the Holocene Epoch (Einsele and others, 2001), which is comparable to the global estimates of carbon currently stored in the soil surface layer (1,350 to 1,576 Pg) and in terrestrial biomass (460 Pg) (Post and others, 1982; Raich and Schlesinger, 1992; Eswaran and others, 1993). Thus, quantification of inland aquatic processes related to carbon, nutrient, and sediment transport is critical for accurately quantifying regional and national carbon budgets and assessing aquatic carbon cycling. Lakes and impoundments (reservoirs and farm ponds) sequester carbon through burial of organic matter in sediments (Cole and others, 2007; Tranvik and others, 2009). Tranvik and others (2009) estimated that global burial of organic carbon in lakes and impoundments may account for 0.6 PgC/yr. Global emissions of CO_2 from lakes and reservoirs have been estimated at approximately 0.8 PgC/yr (Tranvik and others, 2009). Methane emissions from lakes and impoundments could be even more important than CO_2 in terms of GWP. The magnitude of GHG emissions from lakes, ponds, and reservoirs in the United States alone is unknown.

The transport of carbon, sediment, and nutrients to coastal waters stimulates primary productivity and leads to carbon burial in coastal sediments and sequestration in the deep ocean (fig. 2.2*E*). Nutrient additions to coastal systems cause an increase in the CO_2 uptake in coastal systems (van Geen and others, 2000; Hales and others, 2005). Seitzinger and Mayorga (2008) estimated that the carbon production in coastal waters that are specifically fueled by nitrogen loading had a total global estimate of 20 TgC/yr. The fate of this new coastal primary production of carbon and the terrestrial organic carbon exported by rivers is related to both its composition and the rate of sediment supply by rivers (Boudreau and Ruddick, 1991; Hedges and Keil, 1995; Dagg and others, 2004). Finally, this influx of nutrients and coastal productivity can result in the production of significant amounts of CH_4 and N_2O (Bange, 2006; Hirota and others, 2007). The estimates of current carbon stocks and GHG emissions for each ecosystem described above are shown in table 2.1.

Table 2.1. Carbon stocks in the conterminous United States and Alaska, and greenhouse-gas emissions from major ecosystems in the conterminous United States only, as reported by recent studies.

[For each carbon, methane, and nitrous-oxide flux value, a carbon source is indicated by a positive value and a sink is indicated by a negative value. Abbreviations and symbols are as follows: LULUCF, land use, land-use change, and forestry; TgC, teragrams of carbon; TgC/yr, teragrams of carbon per year; $TgCH_4$/yr, teragrams of methane per year; TgN_2O/yr, teragrams of nitrous oxide per year; –, negligible value; NA, data not currently available]

Ecosystem	Carbon stock TgC	Carbon flux TgC/yr	Methane flux $TgCH_4$/yr	Nitrous oxide flux TgN_2O/yr
Forests	57,000[a]	-162[d]	–	–
Grassland/shrublands	16,000[b]	-0.05[d]	0.03[d]	0.09[d]
Croplands	20,000[b]	-8.8[d]	0.1[d]	0.16[d]
Wetlands	62,000[c]	-9.5[e]	3.1[e]	NA
Aquatic habitat[f]	NA	-30 to -40[g]	NA	NA

[a]Source: Goodale and others (2002). Forest and woodland pools include aboveground and belowground live vegetation for trees and understory vegetation, dead wood, litter, and soil organic matter below the litter layer to a depth of 1 meter.

[b]Source: Bliss (2003).

[c]Source: Bridgham and others (2006). This estimate accounts for vegetation and soil organic carbon pools.

[d]Source: U.S. Department of Agriculture (USDA, 2008).

[e]Source: CCSP (2007).

[f]Includes rivers, lakes, and coastal areas. Currently, only carbon-flux estimates from rivers are available at a national level.

[g]Source: Pacala and others (2001). Refers only to lateral flux via rivers.

2.3. Effects of Major Controlling Processes

2.3.1. Effects of Land-Use and Land-Cover Change and Land-Management Change

The examination of carbon sequestration and emissions requires an analysis of changes in both land use (for example, conversion of agricultural land to urban development) and land cover (for example, harvesting trees on a parcel used for forestry). Changes in LULC influence biogeochemical cycles and the carbon and GHG status of an ecosystem (Meyer and Turner, 1992; Houghton and others, 1999). Changes to the Earth's surface that are caused by human activity can have significant effects on ecosystem composition, structure, and function. For example, current global-change studies estimate that approximately 50 percent of the Earth's ice-free land surface has been transformed. This land transformation was caused by major changes in land use and land cover, such as clearing forests for agriculture. If this estimate also included land that was in its "wild" state before being altered by human activity, this number would be much larger (B.L. Turner and others, 2007). When forests or other ecosystems are degraded or cleared, stored carbon is released into the atmosphere. Tropical deforestation alone released roughly 15 to 25 percent of annual global GHG emissions during the 1990s (Gibbs and others, 2007). Changes in LULC generally take two forms: (1) conversion from one land-cover type to another (for example, forest to agricultural use) or (2) modification of a condition within a type (for example, timber harvest with subsequent regeneration of forest).

During the period from 1700 to the 1930s, major LULC changes in the United States occurred when native forests and prairies were converted to agricultural lands. In the 20th century, the trend reversed due to the following: (1) as farms were abandoned, both managed and unmanaged forests were regenerated; (2) the demand for harvested wood for fuel decreased; and (3) fire-suppression methods increased the forest biomass (Houghton and others, 1999; CCSP, 2007). These historical LULC changes were identified mainly by inventory or survey methods, but more current large-scale LULC change studies have been based on a combination of inventories, surveys, and remote-sensing techniques (Meyer and Turner, 1992; Sleeter and others, 2010). Using these methods, studies have shown that there are strong regional differences driving LULC change in the United States. For example, apart from ecosystem disturbance, both agricultural intensification and urbanization have been the major land-use changes in regions such as California during recent decades (Sleeter and others, 2010). In contrast, economic gain fostered an increase in agricultural land cover at the expense of native grasslands in the western Great Plains between 1973 and 1986; however, between 1986 and 2000, public policy, which encouraged native grassland restoration, drove a conversion from agriculture back to grassland (Drummond, 2007). In the Eastern United States, trends, causes, and consequences for LULC change were far more complex. A recent study found that recent LULC changes were associated with forest harvesting and regrowth, agricultural abandonment, and development (Drummond and Loveland, 2010). These findings in LULC changes have significant implications on the capacities of ecosystems to sequester carbon in these regions.

A contemporary driver of LULC change is land management. By applying changes in the types of land management (for example, change in cropland tillage) or in the intensity of land-management activities (for example, active use of prescribed burning), it is possible to manage forests and other ecosystems to enhance carbon sequestration. Recent studies showed that the active use of prescribed burning in fire-dependent forest ecosystems helps to increase the rate of carbon sequestration (Wiedinmyer and Hurteau, 2010). In the Pacific Northwest, increasing the time between harvests and reducing the total number of acres to be harvested are two management activities that would enable forests to store theoretically up to 40 percent more carbon (Hudiburg and others, 2009).

Grassland/shrublands in the Western United States are frequently used for livestock grazing, and the lands store and process far less carbon than forests (Negra and others, 2008); however, with sustainable grazing intensity, grassland/shrublands cumulatively have the potential to sequester a significant quantity of carbon when integrated over approximately 350 million hectares in the United States (Joyce, 1989; Baron and others, 2002; Elmore and Asner, 2006). Reducing grazing intensity also contributes to a reduction in the emissions of N_2O and CH_4 (Baron and others, 2002). Two-thirds of the grassland/shrublands in the United States are identified as having some limits on productivity and carbon storage; therefore, increases in potential soil carbon pools on these lands would be variable and possibly slow (Bruce and others, 1999).

Changes in crop-management practices, such as implementing crop rotation, planting winter cover crops, and setting aside land according to the Conservation Reserve Program (CRP) and Wetland Reserve Program (WRP) agreements, have great potential to increase carbon stock in croplands (McLachlan and Knispel, 2005; Rees and others, 2005; Lal and others, 2007). The CRP offers incentives to encourage the reclamation of former agricultural lands by converting it to other vegetation (often grasses), and this change has resulted in increased carbon storage of approximately 0.6 megagrams of carbon per hectare per year in the United States (Schuman and others, 2002). Additionally, implementation of conservation practices, such as residue management and reductions of summer fallow lands coupled with no-till and reduced-tillage, may be possible land-management activities that may help enhance carbon sequestration and reduce GHG emission in croplands (Tan and others, 2006, 2007). These activities also may help improve soil quality and crop productivity (Causarano and others, 2006).

Land-management activities that affect carbon cycling in terrestrial ecosystems also influence carbon processes in aquatic ecosystems. For example, reservoirs and farm ponds can sequester carbon through the burial of organic matter in aquatic sediments (Cole and others, 2007; Tranvik and others, 2009); the number of farm ponds in agricultural areas of the United States has been increasing 1 to 2 percent annually (Downing and others, 2006). Carbon burial is influenced by rates of erosion and carbon concentration in upland soils, which in turn are influenced by land use. For example, tillage increases the erosion of agricultural land, and sediment resulting from the erosion is deposited in downstream water bodies. Farm ponds can be created to capture sediment that otherwise would enter streams and rivers; however, the utility of farm ponds as carbon-sequestration tools depends on their longevity. Numerous future land-management activities may intentionally or unintentionally alter sediment loads to coastal systems as well. Land-management activities that may positively or negatively affect sediment flux to coastal areas include building new reservoirs, fortifying river channels and banks, and trapping farm sediment (Syvitski and others, 2003). Sediment diverted for inland wetland or floodplain restoration or coastal wetland creation will lower sediment supply to the ocean (Khalil and Finkl, 2009).

2.3.2. Effects of Ecosystem Disturbances

Ecosystem disturbances are episodic events that may affect the composition, structure, and (or) function of an ecosystem (Pickett and White, 1985; E.A. Johnson and Miyanishi, 2001; M.G. Turner and others, 2001). The effects of ecosystem disturbances are treated differently from the effects of global environmental change, which includes sustained alterations in climate that may arise from increasing CO_2 in the atmosphere or nitrogen deposition (B.L.I. Turner and others, 1990). The effects of ecosystem disturbances also are separate from the effects of LULC changes, such as the conversion of forest to cropland. Major ecosystem disturbances are one of the primary mechanisms that have the potential to reset carbon-sequestration pathways and change ecosystems from carbon sinks to sources (Baldocchi, 2008; Running, 2008). Examples of such disturbances include wildland or prescribed fires, hurricanes and storms, and insect or disease outbreaks.

Wildland fire contributes to the loss of stored carbon in terrestrial ecosystems and the release of both CO_2 and CH_4 emissions into the atmosphere (Simpson and others, 2006; Wiedinmyer and Neff, 2007). A study using a global air-sample dataset indicated that burning biomass has contributed to an increase in atmospheric methane levels (Simpson and others, 2006). A study using satellite imagery showed that, between 2002 and 2006, the average annual CO_2 emissions were estimated at 213±50 Tg/yr for the conterminous United States and 80±89 Tg/yr for Alaska (Wiedinmyer and Neff, 2007). The EPA estimated that total CO_2 emissions in the United States from forest fires amounted to 318 Tg/yr in 2007 and 189.7 Tg/yr in 2008 (EPA, 2010). These current estimates of carbon emissions actually may underestimate the amount of carbon historically emitted by fires because fire-return intervals (the number of years between two successive fire events at a specific site or an area of a specified size) actually have increased by an order of magnitude in many areas relative to historic fire regimes (Rollins and others, 2001; Cleland and others, 2004; Grissino-Mayer and others, 2004).

Greenhouse-gas emissions from wildland fires are difficult to estimate because of the temporal and spatial variability of their occurrences, the long-term effects of fires of mixed severity, and the differing degrees of combustion of aboveground biomass and soil organic matter stocks (Neff and others, 2005; Wiedinmyer and Neff, 2007). In the Western United States, an increase in fire-suppression activities during the 20th century is partially responsible for the increase in forest biomass in fire-dependent ecosystems (McKelvey and Busse, 1996; Houghton and Hackler, 2000; Canadell and Raupach, 2008); however, shifts in climate have been correlated with longer wildfire seasons and an increase in the frequency of large fires (those that cover more than 9,400 ha) (Westerling and others, 2006). One result of very large wildfires is that a severe fire season lasting only one or two months can release a considerable amount of carbon dioxide and possibly cancel out the effects of carbon sequestration in forests (Wiedinmyer and Neff, 2007). Because many of these ecosystems are adapted to fire, suppression of wildfires to reduce GHG emissions may not yield greater long-term emissions reductions when compared with GHG emissions from areas where fire is retained or is re-established in its functional ecosystem role.

Other disturbances, such as windstorms or insect outbreaks, do not cause the same direct and rapid emissions of CO_2 as fires, but they do change trees from live carbon sinks to dead and slowly decaying carbon sources over large areas (Running, 2008). In the Eastern United States, strong hurricanes usually occur in two out of every three years. Just one storm can change the equivalent of 10 percent of the total annual carbon sequestrated by forests in the United States into dead and downed biomass (McNulty, 2002). Generally, limited amounts of destroyed timber are salvaged following a major hurricane, and eventually the carbon stored in the trees returns to the atmosphere (McNulty, 2002). Insect outbreaks, such as the mountain pine beetle epidemic in forest ecosystems of the Rocky Mountains, have the same effect. Large amounts of carbon emissions from forests are lost either directly (because live biomass has been converted to dead organic matter) or indirectly (because the death of the forest leads to lost carbon-sequestration capacity). Because of the changing climate regime, these types of insect outbreaks, together with high-severity fires and storm damage, could put forest carbon sinks at risk.

2.3.3. Effects of Climate Change, Elevated Carbon Dioxide, and Nitrogen Fertilization

Climate change, increasing atmospheric CO_2 concentrations, and increasing reactive nitrogen deposition have a strong potential to influence carbon-cycling processes in terrestrial and aquatic environments (Canadell and others, 2007; Reay and others, 2008; McMahon and others, 2010).

The fourth assessment report (AR4) by the IPCC (2007) stated that the best estimates of likely increases in the mean global surface-air temperature by the end of the 21st century are between 1.1°C and 2.9°C for the "low scenario" and 2.4°C and 6.4°C for the "high scenario," and that the major cause of global warming is the human-induced increase of GHG in the atmosphere. Climate change may influence the frequency of extreme events, such as droughts, fires, heat waves, flooding, and hurricanes, thereby releasing additional carbon into the atmosphere. One of the most profound effects of increasing temperatures may be a thaw of permafrost in the northern latitudes (Camill, 2005; Lawrence and Slater, 2005). Climate change can also bring gradual changes to the length of the growing season and shifts in the geographical ranges for some plants (IPCC, 2007). Studies of the effects of climate change on both permafrost and the growing seasons and geographical ranges of plants contain large uncertainties. An increase in the length of the growing season may promote more crop and tree growth, especially of plants in northern regions and higher elevations that act as carbon sinks (Euskirchen and others, 2006; IPCC, 2007); however, many studies indicate that ecosystem respiration has increased due to warming (Bond-Lamberty and Thomson, 2010). Therefore, the carbon loss from ecosystem respiration may substantially reduce or even outweigh the gain from the increase in the length of the growing season (Piao and others, 2008).

Increases in atmospheric CO_2 may enhance crop production and water-use efficiency (WUE; the ratio of CO_2 uptake to evapotranspiration) (Allen and others, 1996). For forests, the Free-Air CO_2 Enrichment (FACE) experiments by Norby and others (2005), tree-ring studies by Soulé and Knapp (2006), and improved field-data analysis by McMahon and others (2010) all suggest that the growth rates for trees may increase with increasing atmospheric CO_2; however, other studies have shown that the magnitude of growth enhancement can vary from 0 to 60 percent when atmospheric CO_2 is doubled (Running, 2008).

Reay and others (2008) studied the possible effects of nitrogen deposition on global carbon sinks; they noted that emissions of reactive nitrogen (Nr; for example, nitric oxide (NO) and nitrogen dioxide (NO_2)) currently are three to five times the global preindustrial levels (mid-1800s) due to fossil-fuel combustion and agricultural activities (Galloway and others, 2004). Under the SRES A2 storyline, worldwide Nr deposition will increase by between 50 and 100 percent by 2030 relative to 2000 (Dentener and others, 2006; Reay and others, 2008). When deposited on land and water, Nr has a stimulating effect on primary productivity in ecosystems that are nitrogen-limited (Vitousek and Howarth, 1991; Elser and others, 2007). On land, an increase in Nr can result in a net increase in forest biomass (and hence, carbon sequestration), except in areas that already receive high levels of atmospheric nitrogen. Similarly, agricultural lands, which often are heavily fertilized, are not expected to see an increase in crop biomass. Increases in primary productivity in oceans can lead to increased burial of organic matter; however, increasing greenhouse-gas emissions from the ocean into the atmosphere may largely offset the carbon-sequestration effect. Reay and others (2008) concluded that carbon uptake by both northern and tropical forests might increase by up to 0.67 Pg/yr and 0.14 Pg/yr, respectively, by 2030. This would amount to an additional 10 percent of projected CO_2 emissions, but the increase was considered to be an upper limit; an increased uptake of 1 to 2 percent of CO_2 emissions was considered more likely (Reay and others, 2008). The enhancement of CO_2 uptake in oceans by nitrogen deposition was estimated to be less than 0.3 PgC/yr (Reay and others, 2008). The potential for increased carbon sequestration in freshwater systems (lakes, impoundments, and wetlands) due to the addition of nutrients was thought to be potentially significant but required further investigation (Elser and others, 2007; Reay and others, 2008).

Complicated interactions exist among climatic and atmospheric factors and among carbon-nitrogen-water cycles. The combined effect (synergies and tradeoffs) of driving forces on an ecosystem biogeochemical cycle and productivity needs detailed analysis. For example, research results based on measurements made at hundreds of European forest-monitoring plots indicate that an increase in carbon-sequestration rates in response to increased Nr deposition will only occur if the site already is nitrogen-limited (de Vries and others, 2009). The AR4 (IPCC, 2007) also indicated that all regions of the world show an overall net negative impact of climate change on water resources and freshwater ecosystems and that water resources will depend on trends in both climatic and nonclimatic factors. Because an increase in carbon sequestration may require more water supplies, tradeoffs between carbon and water resources must also be assessed.

2.4. Carbon Sequestration and Ecosystem Services

In order to properly evaluate appropriate management actions to enhance carbon sequestration, it is important to consider the effects of these actions on ecosystem services. Ecosystem services are the benefits that people and societies derive from the natural processes that sustain ecosystems (Daily, 1997), and they can be generally cataloged into four broad areas: supporting, regulating, provisioning, and cultural (Millennium Ecosystem Assessment, 2003). Supporting services include basic ecosystem functions such as soil formation, whereas provisioning services are important sources of food and fiber. Regulating services help control climate change through carbon sequestration. Cultural services include recreation and education. The concept of ecosystem services is inherently based on the value or importance to humans, but the expression of those services is controlled by the underlying complex ecological structure and processes. (Daily and Matson, 2008; Fisher and others, 2008) (fig. 2.3). In some cases, the links between structure, processes, and resulting services is fairly straightforward. For example, the degree to which a specific plant community can support a given wildlife population can be determined directly by measuring community attributes, such as species composition, height, and age. Other services, such as improving water quality by converting nitrate to nitrogen gas through denitrification, are controlled by more complex interactions between multiple ecosystem attributes (for example, carbon, reduction-oxidation (or redox) status, soil microbial population, and temperature) that are more difficult to measure. These relations also are altered by temporal and condition gradients (fig. 2.3), which result in dynamic processes and significant variability across and within different ecosystems. This makes the relations difficult to measure and quantify at large spatial scales. Ecological production function models based on biophysical inputs are often used to produce spatial estimates of specific services (Nelson and others, 2009).

An explicit recognition of the complex relations among ecosystem structure, processes, and services is critical to understanding the potential ancillary effects of carbon-sequestration strategies. Any change, either anthropogenic or naturally occurring, that affects structural components (such as plant-community composition) or processes (such as nutrient cycling) may affect the quality, quantity, and types of services produced from that ecosystem. The quantification of the effect is a difficult task because some services, such as biodiversity, can be both a cause of the way an ecosystem functions and a response that varies with changing management activities (Hooper and others, 2005; Costanza and others, 2007); therefore, the effects of carbon-specific components may be hard to separate.

Another problem is that the responses of multiple services to specific carbon-related land-management activities are not well studied. Nelson and others (2008) concluded that policies aimed at increasing carbon sequestration did not necessarily increase species conservation and that highly targeted policies were not necessarily better than more general policies. The study by Nelson and others (2008) demonstrates the likelihood that many of the possible management activities and sequestration strategies may affect those ecosystem services that are of direct importance to landowners and land managers. For example, an afforestation plan that is designed to increase carbon sequestration may alter migratory bird habitat depending on the location and the variety of species chosen for that forest (Hamilton and others, 2005; Twedt and others, 2006); therefore, ecological tradeoffs may be necessary when planning land-management activities.

2.5. Ongoing Global and National Carbon and Greenhouse-Gas Inventories and Assessments

Currently, there are many ongoing national and international carbon inventories and assessments. This section describes some of the objectives and methods of these

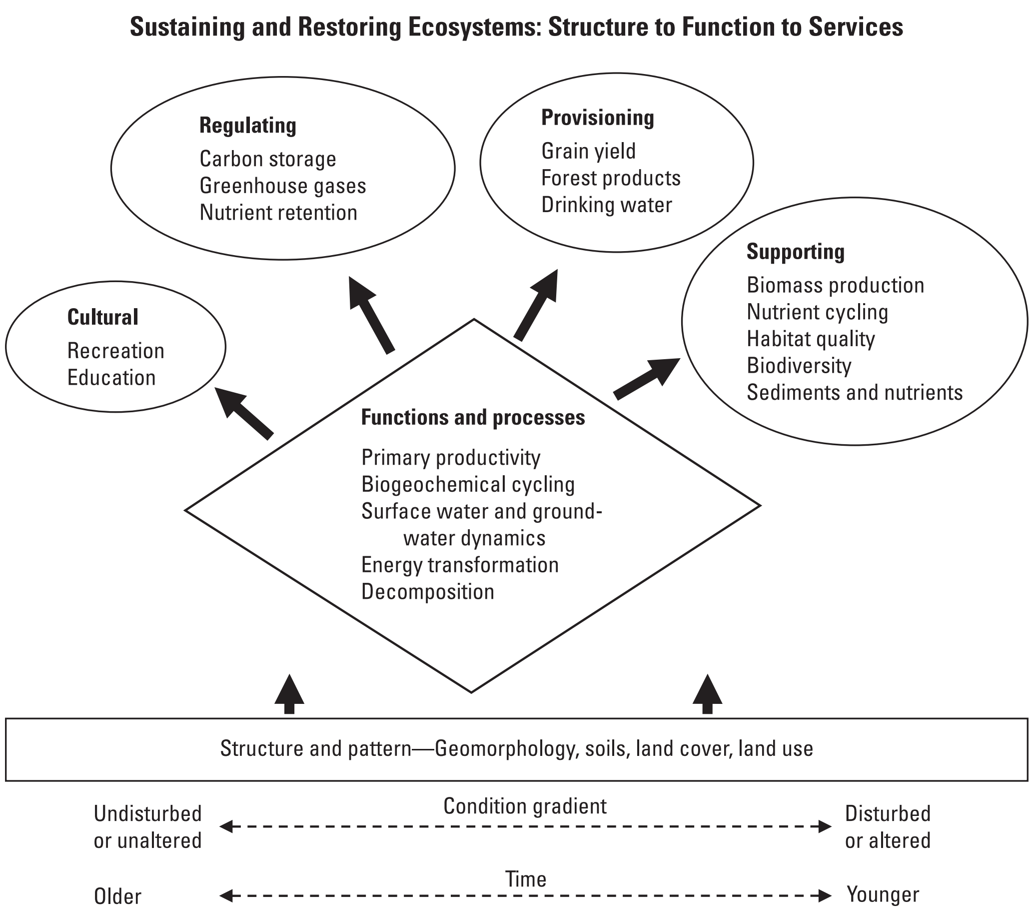


Figure 2.3. Conceptual diagram of the relations among ecosystem structure, function, and services.

large-scale projects. The terms “inventory” and “assessment” are similar in that they both provide estimates of resource conditions; however, the inventory methods focus on measurements of present resource conditions rather than providing an estimate of future carbon-sequestration capacity and GHG fluxes.

2.5.1. Intergovernmental Panel on Climate Change Scenarios and Guidelines

The Intergovernmental Panel on Climate Change (IPCC) is an international scientific body charged with conducting global assessments related to climate change. Since 1990, the IPCC has produced four comprehensive assessment reports (IPCC, 1990, 1992, 2001, 2007). In 2000, a special report on emission scenarios (SRES) was produced by the IPCC (Nakicenovic and others, 2000). The SRES framework provides assumptions about future potential socioeconomic, demographic, and technological changes that serve as storylines or pathways to project future potential GHG emissions and changes in climate. The SRES does not set forth policies that explicitly address climate change; it provides a reference for the evaluation of potential mitigation activities. The SRES includes four main storylines that produce four families of scenarios: A1, A2, B1, and B2. In brief, the A1 family describes a future with fast economic growth, a population increase that peaks in mid-20th century and then declines, and a rapid introduction of new technologies until the middle of the 21st century, after which there is a decline. The A2 family describes a future with economic growth that is tied to regional interests, a slow and steady change in population, and technological adaptation that is not as consistent and widespread as that described in A1. The B1 family describes a future where the economy is focused on the service and information sectors of society; there is a peak in the population with a drop in the middle of the 21st century, as in A1, but this population uses fewer material goods and strives to introduce more environmentally sustainable technologies. Finally, the B2 family describes a world in which there is a focus on developing local economies and promoting environmental sustainability; the population growth is slow, and the development and acceptance of new technologies also are slow. The IPCC projected future emissions and climate change on the basis of the four scenarios in order to allow adequate representation of the inherent uncertainties associated with predicting future climate change.

In 2006, the IPCC published guidelines for agriculture, forestry, and other land uses (AFOLU) that defined three tiers, three different approaches, and two methods for assessing and reporting GHG emissions (IPCC, 2006). The tier 1 method is a basic method that uses default values by LULC type and is most suitable for nations with limited inventory and remote-sensing capabilities. The tier 2 (inventory and bookkeeping) and tier 3 (inventory and process-based models) methods represent more demanding technical capabilities, accuracy, and data requirements. Three different IPCC approaches were described in the guidelines for handling LULC and changes, ranging from simple to more complex treatment of those changes. In describing the approaches, the IPCC recommended six standard AFOLU categories for consistent and comparable reporting: forest land, cropland, grassland, wetlands, settlements, and other land. Finally, the IPCC elaborated on two different methods for GHG emission accounting: the gain-loss method and the stock-difference method.

2.5.2. Examples of Continental-Scale Greenhouse-Gas Inventories and Assessments

Continental-scale inventories and assessments of carbon and GHG have been conducted for various countries and regions in the world; a few examples reported in recent literature are summarized below for Australia, the European Union, and China. In the Australian inventory, carbon storage and GHG emissions (CO_2, CH_4, and N_2O) have been assessed for terrestrial ecosystems by using a prototype National Carbon Accounting System (NCAS; Richards and Brack, 2004). Carbon stocks and GHG fluxes are inventoried and forecasted in spatially and temporally explicit fashions for major ecosystems (such as forests, grasslands, and croplands) by considering major controlling processes, including climate change, soil productivity, land-cover change, soil decomposition, and land-management activities. The NCAS methodology is based on the combined use of Landsat remote-sensing imagery, current and future potential climate-model estimates, soil, inventory, and land-management databases. At the core of the NCAS methodology is an ecosystem biogeochemical (BGC) model that uses accounting algorithms implemented for both non-spatial and spatial applications (Richards and Evans, 2000). Although the prototype NCAS will be enhanced during the next several years, the assessment results have been incrementally reported. In 2007, the most recent year for which reporting was conducted, the net GHG emissions for Australia from agricultural land use, deforestation, and net uptake from forest plantation accounted for 24, 21, and -5.8 TgC, respectively (Australian Government, Department of Climate Change, 2009). The development of a new phase of the NCAS is based on the use of remote sensing for tracking LULC changes and a process-based ecosystem biogeochemical model to estimate GHG emissions (IPCC tier 3 and approach 3 in IPCC (2006)). It is worth noting that the NCAS methodology is used in Australia for both GHG accounting and monitoring purposes.

A recent European Union-wide assessment was conducted for terrestrial ecosystems to assess carbon and GHG (N_2O, CH_4) fluxes into and out of forest and cropland ecosystems. A compilation approach for the assessment used different methods (inventory accounting, process-based ecosystem models, and direct remote sensing) and source datasets (national forest or soil inventory, flux tower, and remote-sensing sources, all of which were collected over a five-year period between 2003 and 2009) (Ciais and others, 2010; Luyssaert and others, 2010). For both forest and cropland ecosystems of the European Union's 25 nations, different carbon pools, fluxes, and processes (such as harvesting, decomposition, and wildfire) were analyzed using the approach. Uncertainties were quantified (where feasible) and communicated following IPCC guidelines. Results from the different methods and datasets then were analyzed and compared, and average values were derived. Results showed that, overall, forest ecosystems in the European Union had an average net primary productivity (NPP) of 520±75 grams of carbon per square meter per year. The total forested area included in this estimate was 1.32×10^6 square kilometers (km^2) to 1.55×10^6 km^2. The net biome productivity (NBP) was 75±20 grams of carbon per square meter per year. For cropland systems, the average NPP ranged between 490 to 846 grams of carbon per square meter per year, and the NBP (estimated by using flux-tower or soil-inventory data) averaged a net loss of 23 grams of carbon per square meter per year. Cropland assessment also considered the N_2O and CH_4 fluxes, which resulted in a combined global warming potential (GWP) range of 42 to 47 grams carbon equivalents per square meter per year (Ciais and others, 2010; Luyssaert and others, 2010). As a result, the study showed that European Union forests and croplands ecosystems are a net carbon sink of 52 grams of carbon per square meter per year.

A recent study on China's carbon balance found that China's terrestrial ecosystems (forests, grasslands/shrublands, and croplands) also were a net carbon sink and averaged between 0.19 and 0.26 PgC/yr (Piao and others, 2009). The study evaluated aboveground vegetation and soil organic carbon by using a methodology in which forest inventory data were (1) analyzed and interpolated together with satellite imagery, (2) calibrated with an atmospheric CO_2 inversion method, and (3) attributed with the use of five process-based models. Because soil data were very limited, the amount of carbon in the soil was estimated by using a regression approach. In addition to estimating the overall carbon-sequestration capacity, the study also reported per-ecosystem estimates of carbon-sequestration capacity and compared those estimates with estimates for the United States, by ecosystem. For example, the study found that aboveground biomass accumulation in forests, on a per-area basis, was 57±26 grams of carbon per square meter per year for China; the same type of accumulation in forests in the United States is reported to be 52 to 71 grams of carbon per square meter per year. Woody encroachment (the invasion of woody plants into grasslands and trees into shrublands) in China was estimated at approximately 30 percent of total forest biomass accumulation. In the United States, woody encroachment represents about 30 percent of the total terrestrial carbon sink (CCSP, 2007). Overall, the study noted that the total terrestrial carbon sink of China is comparable to that of continental Europe but is about half the size of the sink in the United States. One significant weakness, as noted in the report, was that the study did not account for land-use change, which is a significant factor for China (Piao and others, 2009). These studies indicate the global-scale impact from biological carbon sequestration and possible methods and techniques to follow to produce a successful assessment. Additionally, it is useful to compare carbon stock numbers from ecosystems in different parts of the world. Table 2.2 compares the forest stocks from studies in China and the European Union to forest stocks from the United States.

Table 2.2 Comparison of forest stocks and net forest-stock changes from three continental-scale studies of temperate forest zones.

[Abbreviations are as follows: M km^2, millions of square kilometers; PgC, petagrams of carbon; TgC/yr, teragrams of carbon per year]

Study regions	Forest area (M km^2)	Stocks (PgC)	Net forest stock change (TgC/yr)	Uncertainty (percent)
China	1.75	27.1[a]	-92[b]	47[b]
European Union	1.46	23.1[a]	-110[c]	27[c]
Conterminous United States	2.69	41.3[a]	-162[d]	18[d]

[a]Source: Goodale and others (2002). Forest and woodland pools include aboveground and belowground live vegetation for trees and understory vegetation, dead wood, litter, and soil organic matter below the litter layer to a depth of 1 meter.

[b]Source: Piao and others (2009). Pools included in their stock change estimate are not clear.

[c]Source: Luyssaert and others (2010). Pools included in their stock change estimate are not clear

[d]Source: U.S. Environmental Protection Agency (EPA) (2010). Pools included in the stock change estimate are aboveground and belowground biomass, litter, and soil organic carbon.

2.5.3. Existing National-Scale Inventories and Assessments in the United States

As of 2006, the United States has been identified as the world's second largest cumulative national source of fossil-fuel-related CO_2 emissions with a source of 1.6 Pg of carbon (Marland and others, 2009). A considerable amount of work already has been done within the United States to account for the potential effect of ecological carbon sequestration in offsetting these emissions. The most comprehensive assessment related to the carbon cycle and budget is that of the first State of the Carbon Cycle Report (SOCCR) (CCSP, 2007), which is discussed above in section 2.2. Two other ongoing national-scale studies also contribute to the state of knowledge about the Nation's carbon and GHG in ecosystems: the EPA's annual U.S. Greenhouse Gas Inventory Report (EPA, 2009, 2010), and the U.S. Forest Service's Forest and Rangeland Renewable Resources Planning Act (RPA) assessment (U.S. Department of Agriculture (USDA) Forest Service, 2000), which is conducted on a 10-year cycle.

In the EPA's annual GHG inventory reports (EPA, 2009, 2010), GHG emission estimates are reported from a range of sectors including energy, industry, waste, LULC, forestry, and agriculture. The primary data sources for the annual emission reports related to LULC, forestry, and agriculture are the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service (USFS) and the National Resources Inventory (NRI) of the National Resource Conservation Service (both within the USDA); these databases are augmented by the National Land Cover Database (NLCD) produced by the Multi-Resolution Land Characteristics Consortium (MRLC) (Homer and others, 2004). Because of the source data used, the annual GHG inventory reports were compiled using a tier 3 and approach 2 methodology, according to the IPCC (2006) terminology. The estimates in the GHG inventory reports address land-use change, as well as carbon emissions from agricultural and forest fires on managed lands. Alaska and Federal lands in Hawaii are not included in the current reports.

The USDA also produces periodic GHG inventory reports, which are incorporated into the EPA's annual inventories. The most recent agriculture and forestry greenhouse gas inventory (USDA, 2008) spans the time period from 1990 to 2005, and it complements EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA, 2007). The USDA report provides a more in-depth review of emissions from forestry and agricultural lands in the United States than what is presented in the EPA reports. The USDA relies on the Century (Parton and others, 1993) and Daycent (Parton and others, 1998) ecosystem models to estimate direct and indirect GHG emissions for major croplands in the United States. These models simulate fluxes of carbon and nitrogen between the atmosphere, vegetation, and soil for croplands and grazing lands. Carbon emissions from forests are estimated using the FORCARB2 model. The NRI (USDA, 2009) is an important data source for USDA's greenhouse-gas-emission inventory for the United States.

The annual FIA program conducted by the USFS provides the Nation with the most extensive and intensive in situ data about forest, species composition, timber volume, aboveground biomass, LULC classes, various ecosystem services (for example, water supply and wildlife habitat conditions), and other variables (W.B. Smith, 2002; Birdsey, 2004; W.B. Smith and others, 2009). The FIA visits between 15,000 and 60,000 plots annually across the Nation. Soil and forest health data also are collected in the FIA database, but are not as extensive as some of the other data variables. Using the FIA database as the primary data source, the USFS conducts an assessment of forest and rangelands resources every 10 years, as required by the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) (U.S. Congress, 1974). The two most recent RPA-mandated assessments (1990 and 2000) focused on present and future resource conditions, productivity (including forest carbon), sustainability, and economic demand of forest and rangeland ecosystems (Powell and others, 1993; Langner and Flather, 1994; Joyce, 1995; Dwyer and others, 2000; Joyce and Birdsey, 2000; W.B. Smith and others, 2001, 2009; Alig and others, 2003). The upcoming 2010 RPA-mandated assessment will continue to assess resources and impacts and pressure on resources from climate change, LULC change, and global supply and demand. Although reports are not yet available, several distinct characteristics of the 2010 RPA assessment have been provided as below:

- Global effects on U.S. forest resources and trends will be considered by integrating forest-product models within a larger global forest model.
- Effects of climate change will be addressed in resource analyses, including projections of forest resources, wildlife habitat effects, and water supply.
- Analysis of forest resources will incorporate three future IPCC scenarios to address the climate change, LULC change, and uncertainty associated with the assessment.

2.5.4. Uncertainty Assessment and Reporting in Existing National Assessments

An evaluation of uncertainty is a critical component of resource assessments and is necessary in order for an assessment to be translated into information that is useful for formulating policy. In addition, when complex models are used as a basis for evaluating policy or management alternatives, it is important that the models are consistent, accurate, verifiable, and transparent (Prisley and Mortimer, 2004). Therefore, model validation and verification approaches, such as sensitivity analysis and expert review, are recommended.

The IPCC (2006) recommended techniques to develop estimates of uncertainty for GHG reporting and guidance for incorporating these techniques These estimates may be developed from measured data, published information, modeling approaches, and expert judgment. One widely used modeling approach is Monte Carlo simulation. Here, variables in a model are assumed to have probability distributions rather than single deterministic values; models are run multiple times and draw parameters from distributions of possible values. For example, IPCC (2006) identified a range of popular distribution functions that might be used in a simulation. The outcomes from multiple runs of the model provide a distribution of results, thereby allowing the variability of results to be quantified. In an example of this type of evaluation, Heath and Smith (2000) conducted a Monte Carlo simulation of the national forest carbon budget and reported that carbon stocks had uncertainty levels of ±10 percent, although fluxes had confidence intervals of 50 to 100 percent. Because many biophysical parameters (such as soil characteristics and forest growth) are not independent, but rather are strongly related, it is important to account for covariability among parameters as well. J.E. Smith and Heath (2001) found that distributional forms for variables were less important than covariability between parameters.

Several recent assessments of different aspects of GHG flux serve to illustrate viable techniques for uncertainty assessment and provide the results from similar efforts. Table 2.3 summarizes some of the carbon-sequestration quantities and uncertainties from recent studies.

Some general lessons can be learned from these and other assessments. Uncertainties expressed as relative terms (as a percentage of a mean estimate) tend to be higher for small pools and fluxes (as noted above). Fluxes tend to have higher relative uncertainties than stocks, and estimates for detailed subcategories (for example, specific pools or components) have higher relative uncertainties than broadly aggregated categories. Similarly, geographic aggregation serves to lower relative uncertainties. As an example, in the spatial aggregation of forest-inventory data, an estimate for a State has a lower uncertainty than the collective estimate for the survey units (regions that make up the State) (Reams and others, 2005). For example, Kim and McCarl (2009) described the use of the reduction in the coefficient of variation (an uncertainty measure related to confidence interval) when conducting an assessment, because estimates were aggregated progressively from a county to a region to a State.

In the examples described above, uncertainty of carbon stocks and flux estimates is characterized by the use of confidence intervals. Spatially explicit modeling approaches also can characterize uncertainty in a spatial model or a map. In such cases, spatial patterns and relationships in uncertainty can be examined, which could lead to insights in model validation and improvement. For example, Blackard and others (2008) developed percent-error maps to graphically depict the spatial distributions of the variability of estimated biomass.

2.5.5. Economic Analysis and Its Use in Existing National Assessments

Climate-change mitigation assessments focus on the future ability of a system to sequester carbon and reduce GHG emission. Climate-change mitigation policy analyses often estimate a sector of society's capacity to abate climate change. Some approaches include the specific analyses of proposed legislation (for example, EPA, 2009; Larsen, 2009; Ross and others, 2009) or approximations of national levels of commitment to incentives, investments, regulatory reforms, and urgency for action (Creyts and others, 2007). From a policy perspective, carbon sequestration by ecosystems is one of many types of climate-change mitigation.

Economic analyses, including those that concern climate-change mitigation assessment, can be differentiated in terms of scope. The narrowest and generally more detailed analyses are those of a single sector or a single market. Conversely, the most comprehensive analyses attempt to capture economy-wide effects, but this often comes with a loss of detail. The following studies exemplify this compromise between scope and detail. An econometric model (Lubowski, 2006) operates at the unit of private parcel of land. It accounts for land-use decisions; for example, the incentive for land conversion to forest based on a carbon subsidy for growing trees. The model assumes that landowners choose to maximize the present value of expected net benefits from the land and base their expectations of future land-use profits on historical and current subsidy levels. Looking at the agricultural sector, Lewandrowski and others (2004) adapted the U.S. Mathematical Programming Regional Agricultural Sector Model to analyze the performance of alternative incentive designs (for example, cost shares) and payment levels (for example, carbon price) paid to farmers for adopting land uses and management practices that increase the storage of carbon in soil.

In order to capture sector details, yet retain economy-wide scope, the EPA applies a set of interactive tools to analyze climate-change mitigation strategies and the ensuing effects. These models include the Forest and Agriculture

Table 2.3. Selected estimates and uncertainties reported from recent national-scale assessments of carbon sequestration.

[SOCCR, first State of the Carbon Cycle Report (U.S. Climate Change Science Program (CCSP), 2007); Pg, petagram (1 billon metric tons); CO_2, carbon dioxide]

Assessment and source	Assessment components	Geographic scope	Quantity (stock or flux)	Uncertainty (95 percent confidence level)
EPA (2010)	Forests and harvested wood	Conterminous United States	0.8 Pg CO_2 equivalent (annual sequestration)	±18 percent
Sundquist and others (2009), a rapid assessment of carbon sequestration	Soil organic carbon	Conterminous United States	73.4 Pg carbon (storage)	±30 percent
Sundquist and others (2009), a rapid assessment of carbon sequestration	Forest biomass carbon	Conterminous United States	17.0 Pg carbon (storage)	±20 percent
CCSP (2007), SOCCR	Forest carbon	United States	0.3 Pg carbon (annual sequestration)	±50 percent
CCSP (2007), SOCCR	Wood products	United States	0.06 Pg carbon (annual sequestration)	±50 percent
CCSP (2007), SOCCR	Wetlands	United States	0.02 Pg carbon (annual sequestration)	± >100 percent

Sector Optimization Model with Greenhouse Gases (FASOM-GHG; Murray and others, 2005), which is a partial equilibrium model that can evaluate joint economic and biophysical effects of GHG mitigation scenarios in the U.S. forestry and agricultural sectors. The Applied Dynamic Analysis of the Global Economy Model (ADAGE; Ross and others, 2009) is a computable general equilibrium model that can estimate policy effects while accounting for all interactions between businesses and consumers. Such economy-wide models generally seek to explain the behavior of supply, demand, and prices in a whole economy that has several or many interconnected markets. As an example, the FASOM-GHG model indicates that increasing the quantity of forest acreage dedicated to carbon sequestration has implications for current and future industrial forest production and prices, and for agricultural production and prices. Next, the ADAGE model indicates that these price and production changes generate feedback through the broader market. Finally, the FASOM-GHG model indicates that this feedback affects the forest and agricultural sectors.

The above-mentioned policy models capture (to varying degrees) the competing land uses for carbon sequestration, food, timber, and biofuel-energy-crop production. Although the policy models help decisionmakers understand the economic influences on resource capacity, they currently are not adequate for an understanding of the biophysical capacities of carbon sequestration in all disturbed ecosystems under a range of climate scenarios. Also, the policy models tend to be concerned with resources on private lands, although a public-lands policy model for forests recently has been developed that can be coupled with FASOM-GHG (Darius Adams, Oregon State University, written commun., 2009).

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3. Methodology for the National Assessment

3.1. Introduction

This chapter introduces the scope of the methodology, a framework for assessing carbon and other GHG fluxes, and specific methods for the assessment. Detailed discussions about the framework and specific methods are provided in the appendixes.

3.1.1. Design Requirements and Goals for Assessment

This section describes the integrated suite of methods necessary to conduct an assessment of carbon stocks, carbon-sequestration capacity, and fluxes of GHGs (CO_2, CH_4, and N_2O) in the Nation's ecosystems, as mandated by the EISA (U.S. Congress, 2007) (see chap. 1). In assessing these GHGs, the EISA requires an examination of the effects of controlling processes (land-use and land-cover changes and ecosystem disturbances are two major controlling processes for GHG fluxes), and the potential for land-mitigation activities to increase carbon sequestration and reduce GHG emission over time. Carbon sequestration and GHG emissions in natural and managed ecosystems are the result of complex interactions among land use, land cover, management activities, ecosystem compositions and structure, natural and anthropogenic disturbances, and biogeochemical processes. Thus, to perform the assessment and meet the requirements of the EISA, an integrated multidisciplinary methodology is needed based on the following design considerations:

- Assess GHG fluxes and carbon-sequestration capacities comprehensively by considering all major pools, stocks, flux types, and controlling processes for all national lands and aquatic ecosystems of the 50 States. Incorporate key processes or factors that affect carbon cycling and GHG emissions, such as land-use and land-cover changes, ecosystem disturbances (for example, fire), lateral fluxes, and management activities. The comprehensive nature of the assessment should lead to an improvement in the quality of the assessment and a characterization of the uncertainties in the assessment results (Loveland and DeFries, 2004; Running, 2008).
- Assess both present and future GHG fluxes and carbon-sequestration capacities and produce annual estimates for 50 years, from 2001 to 2050. An evaluation of future potential ecosystem carbon and GHG conditions will be based on a framework of reference and alternative enhanced land-cover and management scenarios that are calibrated and reported at the regional scale. The first 10 years of the assessment (2001–2010) will provide current carbon storage and GHG production conditions, while also enabling calibration, validation, and estimation of uncertainties. The next 40 years will be used to project future potential changes in carbon storage, carbon sequestration, and GHG fluxes. Assessment over the 50 years will permit an examination of complex interactions among climate change, land cover, land management, and other controlling processes.
- Conduct the assessment at a spatial resolution sufficient to evaluate process-level connections between land use, land cover, management, climate, and site-specific properties such as soil type, hydrology, and topographic setting. Thus, the assessment will be spatially explicit for the purpose of capturing the variety of processes that exist in heterogeneous landscapes and thereby will provide GHG flux and carbon-storage results that are meaningful when aggregated and compared over broad areas, such as a region or a State. The spatially explicit methods also will provide a greater understanding of geographic distributions of ecological carbon sequestration by pools and flux types.
- Investigate links between (1) potential land-use and land-cover change and land-management activities, and (2) future carbon storage and GHG fluxes in ecosystem and ancillary effects (for example, ecosystem services and costs). This analysis will permit decision-makers and other stakeholders to evaluate the effects of mitigation strategies on future potential ecological capacities for carbon sequestration and GHG flux while also considering the potential unintended consequences within or between other ecosystems.
- Identify and collaborate with other existing national programs that evaluate carbon storage and GHG fluxes. Use common data, assumptions, and scenarios as much as possible for this assessment in an effort to minimize inconsistent or conflicting results. Portions of existing national programs, such as the U.S. Environmental Protection Agency (EPA) national emissions inventory and the U.S. Forest Service's RPA-mandated assessment, overlap with parts of this assessment, thus creating an opportunity to enhance consistency between this assessment and other, more specific programs.
- Assimilate appropriate in situ and observational data to constrain methods and models and to evaluate uncertainty. Efforts will be made to include suitable data or models in order to further reduce uncertainty. In situ data (for example, the FLUXNET database; Running and others, 1999; Baldocchi and others, 2001) are commonly used for resource and GHG-flux assessments. To the extent possible, these and any other appropriate datasets will be incorporated, such as those containing biophysical data (for example, soils, climate) and data derived from remote-sensing methods (such as land-cover change, wildland fires, or vegetation indices).

Judgments as to the suitability and use of input data will be made on a case-by-case basis as the assessment proceeds.

3.1.2. Methodology Scope

This section describes the scope of the assessment, including definitions of pools and flux types, assessment units, ecosystems, temporal scales, and spatial scales.

Scale of Assessment and Reporting: Assessment Units.— Operational logistics require that the assessment be separated into several individual units to stratify data collection and modeling efforts, plan and prioritize the assessment, and report results. The assessment and reporting units will correspond to Level II EPA ecoregions (Omernik, 1987, 2004). The Nation includes 24 large Level II EPA ecoregions (fig. 3.1), and assessment results will be provided for each ecoregion. Components of the aquatic assessment will be stratified using watersheds that are aligned, to the extent possible, with the boundaries of the ecoregions.

The use of the EPA Level II ecoregions as units of the assessment defines the scale for reporting the assessment results because it is within each of these ecoregions that the scenarios will be developed and the results will be analyzed (including validation and uncertainty analysis) and reported. Below this scale, data products may still be useful because many data products are geographic information system (GIS) maps that are generated at a pixel size (map resolution) of 250 meters (m) using spatially explicit models. However, the map resolution does not designate a scale of the assessment. The scale of the methodology is set as assessment units. Users are encouraged to explore further validation and uncertainty measures in order to address scaling and other effects when using GIS map data.

Ecosystems.—The EISA requires the assessment of carbon storage, carbon sequestration, and GHG fluxes in and out of the Nation's ecosystems. For the purpose of this

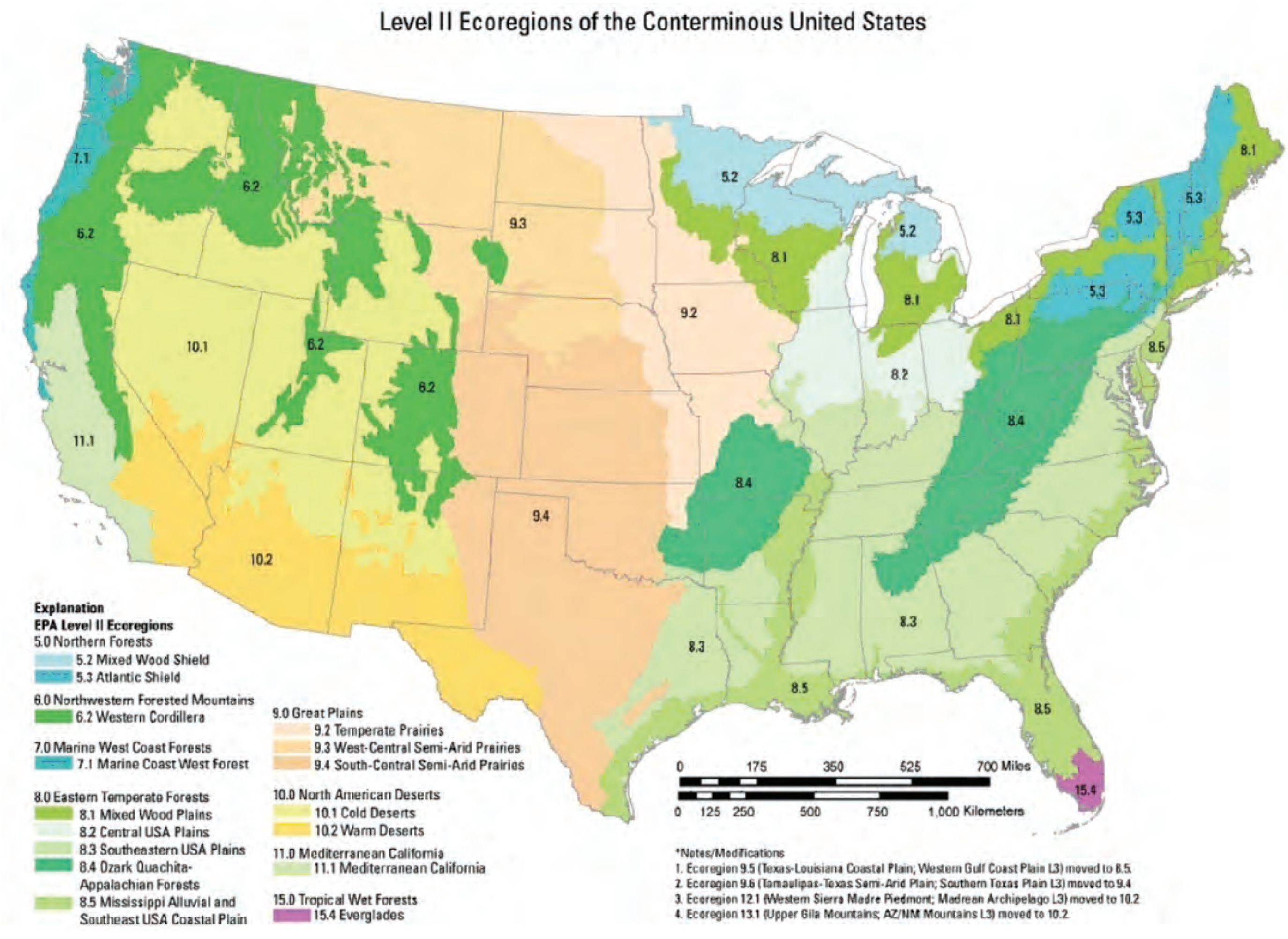

Figure 3.1. Map showing Level II ecoregions of the U.S. Environmental Protection Agency, modified from Omernik (1987) for this report and for the assessment. Only the conterminous United States is shown. This ecoregion framework will be used as the basis for the assessment units, and the ecoregions will be used as assessment units for purposes of planning, prioritization, analysis, and reporting.

methodology for the assessment, the ecosystem terms used in this report are defined as broad types of forests, grassland/shrublands, croplands, wetlands, and aquatic habitats (table 3.1). The use of these broad biome types for ecosystem classification follows the intent (but not the actual terminology) of the U.S. Climate Change Science Program (now U.S. Global Change Research Program) “State of the Carbon Cycle Report,” Part III, Land and Water Systems (U.S. Climate Change Science Program, 2007). Because this assessment is conducted at the ecoregion scale, the ecosystems defined above will be assessed and analyzed on the basis of their unique regional characteristics.

Within each assessment unit, ecosystem boundaries will be determined by using the 2001 National Land Cover Dataset (NLCD, Homer and others, 2004) and other datasets such as the National Wetland Inventory (NWI, Cowardin and others, 1979). These datasets, which have comparable definitions for various ecosystems, will be crosschecked and used in the assessment to help define the spatial boundaries of the ecosystems (table 3.1). Further discussion about spatial boundaries for the ecosystems may be found below in section 3.2, “Methodology Framework.”

Pools and Flux Types.—Production, consumption, and transitions of carbon among seven pools (table 3.2) will be assessed in order to account for carbon stocks and GHG fluxes. The methodology includes the five primary carbon pools and a harvested wood pool that are defined and recognized by the IPCC (Penman and others, 2003; IPCC, 2006) and are most commonly used for other national GHG inventories (for example, U.S. Climate Change Science Program, 2007; U.S. Environmental Protection Agency, 2009). Unique to the methodology for this assessment is the inclusion of a lateral flux pool, which accounts for carbon that is exported by rivers and streams and is used to evaluate the effects of terrestrial management on carbon storage and GHG production in inland and coastal waters. The relations between the carbon pools and the fluxes of carbon and nitrogen to be assessed are illustrated in figure 3.2.

The net ecosystem exchange (NEE) is the net flux or uptake of carbon (CO_2 and CH_4) or nitrogen (N_2O) between the ecosystem and the atmosphere. The primary processes in determining NEE are (1) net primary productivity (NPP, which is calculated by subtracting autotrophic respiration from photosynthesis), (2) fluxes from heterotrophic respiration (HR), (3) fire, and (4) the production of biomass commodities (for example, wood products). The net ecosystem carbon balance (NECB) accounts for all physical, biological, and anthropogenic sources and sinks (for example, photosynthesis and the lateral movement of dissolved organic carbon (DOC), inorganic carbon (DIC), and particulate organic carbon (POC)) (fig. 3.2).

Mitigation Activities.—Changes in carbon stocks and fluxes in the seven pools are affected by mitigation activities of two types: land-use change and land-management change. Mitigation activities within this scope directly increase carbon sequestration in soils, vegetation, wood products, and sediments. The following items are not included when considering mitigation activities: (1) indirect effects from the generation of energy from biomass; (2) technological actions that can aid in ecologically sequestering carbon, but that are not explicitly land-use or land-management changes (for example, growing algae in industrial fluxes); (3) activities to reduce downstream or life-cycle GHG fluxes (for example, GHG emissions from hauling and processing of timber are not assessed for harvest rotation changes); and (4) GHG emissions from livestock.

Assessment Timeframe.—The assessment will be conducted in annual time steps from 2001 to 2050. This timeframe meets the legislative requirements for assessing annual present and future ecosystems capacities and addresses the following considerations. The 2001 starting year was selected because the National Land Cover Database (NCLD) 2001 (which describes the general land cover of the Nation) and the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) dataset (which describes vegetated ecosystem composition, structure, succession state, and wildland fire disturbances) were both available during that year. The two datasets will provide the starting point for modeling future land changes, disturbances, and GHG fluxes into and out of ecosystems. The data for years between 2001

Table 3.1. Ecosystems, descriptions, and thematic components of source datasets.

[The use of the 2001 National Land Cover Dataset (NLCD) and other datasets helps to define spatial boundaries of the ecosystems at a regional scale. Other abbreviations are as follows: NHD, National Hydrography Dataset; NID, National Inventory of Dams; DLG, digital line graph; NWI, National Wetland Inventory]

Ecosystem	Included land-cover type (and dataset source)
Forests	Deciduous, evergreen, mixed, and disturbed forests (NLCD).
Grassland/shrublands	Shrub/scrub and grassland/herbaceous classes, as well as Alaska-specific areas mapped as sedge/herbaceous, lichens, and moss (NLCD).
Croplands	Cultivated cropland, irrigated land, and pasture/hay classes (NLCD).
Wetlands	Combinations of NLCD wetland classes and NWI wetland classes (for example, palustrine wetland).
Aquatic habitats	Lakes, impoundments, estuaries, coastal waters, ponds, rivers, and other inland water bodies (combined use of NLCD, NHD, NID, DLG, and NWI).

Table 3.2. Broad-level definitions of relevant carbon pools to be included for carbon-assessment products.

[Definitions for all but harvested wood and lateral flux are adapted from Intergovernmental Panel on Climate Change (IPCC) (2006). Abbreviations are as follows: mm, millimeter; cm, centimeter; DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; POC, particulate organic carbon]

Pool	Description
Living biomass	
Aboveground biomass	All biomass of living vegetation, both woody and herbaceous, above the soil, including stem, stump, branches, bark, seeds, and foliage.
Belowground biomass	All biomass of live roots. Fine roots of less than 2-mm diameter often are excluded because often they cannot be distinguished empirically from soil organic matter or litter.
Dead organic matter	
Dead wood	All nonliving woody biomass not contained in the litter, either standing, lying on the ground, or in the soil or sediments. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter.
Soils/sediments[1]	
Litter and deadwood	All nonliving biomass with a diameter less than the minimum diameter chosen for dead wood (10 cm), lying dead, in various states of decomposition above mineral or organic soil or sediments. Includes the litter layer as usually defined by soil typologies. Live fine roots less than 2 mm in diameter where they cannot be distinguished from it empirically.
Soil organic matter	Organic carbon in mineral and organic soils and sediments to a specified depth chosen for the assessment and applied consistently through the time series. Includes live fine roots less than 2 mm in diameter where they cannot be distinguished from it empirically.
Harvested wood	
Wood	Harvested wood from forests.
Lateral flux	
Dissolved organic and inorganic carbon; particulate organic carbon	DOC, DIC, and POC that are exported by surface waters, and POC that is stored in inland and coastal waters.

[1]Inorganic carbon stocks (such as calcium carbonate) in mineral soils and sediments will be estimated using the Soil Survey Geographic (SSURGO) database (http://soils.usda.gov/survey/geography/ssurgo/) (see section 3.3.1 of this report); however, given the uncertainty in modeling formative processes in relation to land use as well as tracking vertical and lateral leakage processes, future potential changes in inorganic carbon stocks will not be modeled.

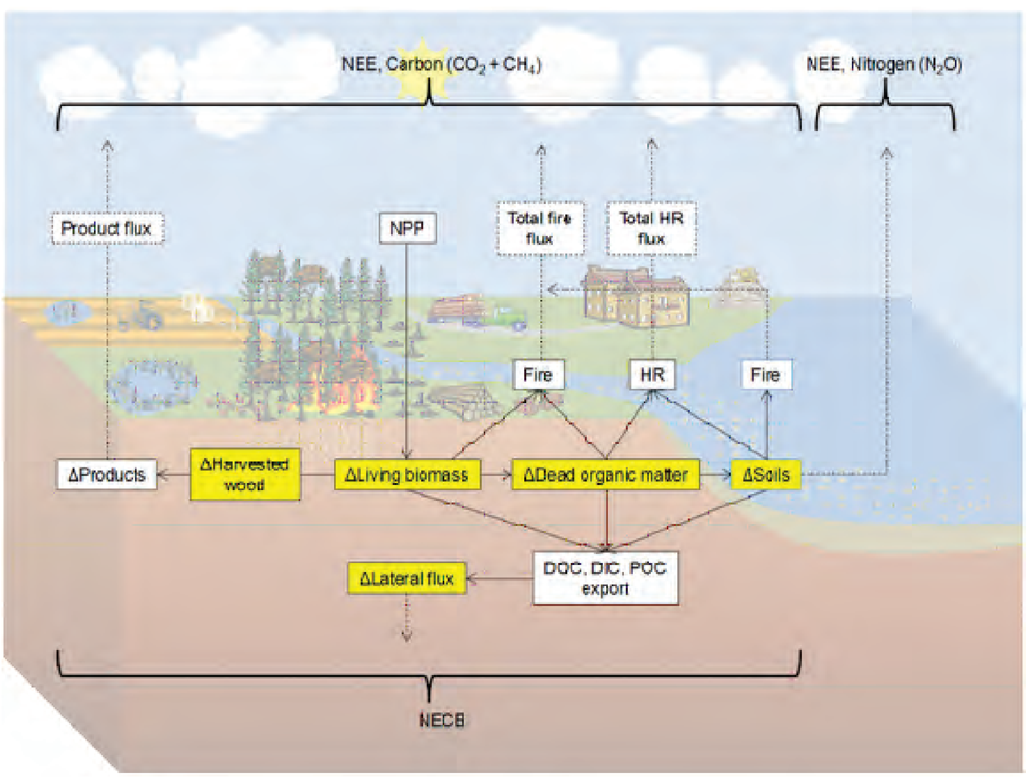

Figure 3.2. Diagram showing fluxes of carbon (as carbon dioxide and methane) and nitrogen (as nitrous oxide) and exchanges among the seven primary carbon pools (yellow boxes). Abbreviations are as follows: CH_4, methane; CO_2, carbon dioxide; DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; POC, particulate organic carbon; HR, heterotrophic respiration; NECB, net ecosystem carbon exchange; NEE, net ecosystem exchange; N_2O, nitrous oxide; NPP, net primary productivity. Small triangles in yellow boxes are deltas, which indicate "change in." For more information about these terms, see Chapin and others (2006).

and 2010 will offer opportunities to assess current ecosystem carbon stocks, sequestration rates, and GHG fluxes and will be used for the model design and the calibration and validation of results. The selection of 2050 as the endpoint was influenced by two considerations: (1) Uncertainties associated with scenarios, data, and methods will increase with time. Limiting the assessment to 2050 will help constrain such uncertainties. (2) The EISA does not specifically define a time horizon for the assessment, but an assessment over a 50-year time frame should provide adequate information for policy and management applications.

3.1.3. Methodology Constraints

Comprehensive national-resource assessments are usually limited by many constraints, including the scope of the assessment, data availability, technological developments, established scientific concepts and methods, available project time, and resources. These limitations apply to this assessment as well. Given that this methodology has been developed to fulfill the EISA's legislative requirements, the limitations inherent in this process need to be discussed:

- The scope of the methodology and assessment will be limited to the requirements set forth by section 712 of the EISA, as detailed in chapter 1.
- Consistency at the national level is needed, such that quality, inherent variability, and uncertainty of results are comparable among regions and contain minimum biases when compared with known reference data (such as national inventory programs). Scenario construction and methods for assessment also must be transparent in order to maintain consistency in interpretation.
- Established and simplified methods and models that incorporate datasets of national coverage will be used in the assessment. The assessment needs simplified dependencies between technical components to permit effective coupling of methods and models. Areas where established methods or models are limiting will be prioritized for research treatment by others.
- Availability of in situ, mapped, and remotely sensed data is uneven for the national assessment. The GHG flux data are especially uneven. The methodology is designed to circumvent, where necessary, issues of poor data availability or quality by using surrogate data and appropriate available techniques for calculation. Ultimately, the quality and availability of input data will affect the quality and uncertainty of the assessment.

3.1.4. Collaborations for the Assessment

Many Federal agencies, nongovernmental organizations, and international entities already have developed unique inventory, assessment, and research programs in support of their policy and science needs for understanding the carbon cycle and processes and for mitigating GHG fluxes. Where appropriate, these ongoing programs will play important roles for this assessment, including (1) active collaborations for conducting the assessment, and (2) review, feedback, and use of results of the assessment. As discussed below in the methodology descriptions, a successful implementation of the methodology will depend on the extent to which this assessment is developed collaboratively. Important areas of collaboration for the assessment are described below:

- Data sharing—In situ reference data (such as national inventory programs, flux-tower data, informal networks, and location- or ecosystem-specific GHG-flux data) are critical in order to constrain methods and models for estimating current and future potential carbon and GHG fluxes. Data about land management and their associated costs are required in order to construct potential mitigation actions and to analyze tradeoffs between the management of carbon and other ecosystem services.
- Review of methods and results—A rigorous scientific review process will set the foundation for the assessment. Throughout the methodology development process and the assessment, the science community (such as the North America Carbon Program) and agency research programs will be engaged both for the review of this method and the assessment, and for the opportunity to compare methods and models.
- Participation—The quality and usefulness of the assessment will benefit greatly from participation by individual investigators, agency programs, and stakeholders. For various methods and data needs, agencies and organizations have roles to play, including that of providing assessment components, models, and data. In addition, stakeholders, such as land managers in various regions, may find that participation in regional consultation processes for constructing mitigation scenarios will benefit their organization's missions. Encouraging broad participation by stakeholders in the use of assessment results is critical to the ultimate value of this assessment effort.
- Enhancing consistency—Agencies or organizations that play active roles in resource assessment will be actively consulted throughout development of the methodology and the assessment. Consistency between this assessment and other national programs will be enhanced by (1) using the same high-quality in situ data, and (2) using comparable scenarios or assumptions.

3.1.5. Methodology Organization

As discussed above, the EISA requires the national assessment to consider carbon-sequestration capacities and GHG fluxes for both terrestrial and aquatic ecosystems. The assessment also will address major controlling processes that affect present and future carbon storage and GHG fluxes in order to support a range of policy and management applications. The organization of this methodology document addresses each of these issues in turn:

- An approach for assessing present carbon storage in ecosystems and GHG fluxes that is consistent with both existing accounting guidelines and the subsequent methods presented.—Years 2001 through 2010 are considered in order to determine the current carbon storage and rates of flux and carbon sequestration.
- An approach for assessing future carbon storage in ecosystems and GHG fluxes.—The scenario framework for years 2011 through 2050 will link future potential climate and socioeconomic projections with the design of future potential mitigation activities (for example, potential land-use and land-management changes to enhance carbon-sequestration capacity).
- A set of methods that supports the assessment of both present and future potential conditions.—The methods are (1) mapping and modeling of current and future land use and land cover, (2) characterizing and modeling present and future ecosystem disturbances, (3) estimating and modeling carbon storage and GHG fluxes from terrestrial and aquatic ecosystems, (4) syntheses of mitigation scenarios (including ecosystem services and cost), and (5) validation, uncertainty analysis, and monitoring.

3.2. Methodology Framework

This methodology is designed for a comprehensive assessment of current and future potential carbon stock, carbon sequestration, and GHG fluxes. Assessment results will be produced for the years 2001 through 2050. The results for years 2001 through 2010, which are based on past and current input data, will be used to estimate the current carbon and GHG conditions. Future potential carbon stocks, carbon sequestration, and GHG fluxes will be modeled and estimated for 2001 through 2050 for a range of future mitigation scenarios aligned within three IPCC scenarios (discussed later in this section).

The framework incorporates recommendations of IPCC's good practice guidelines for the assessment of carbon and GHG for land use, agriculture, and forestry (Penman and others, 2003). The methods to be used for the assessment are based on extensive observational data, as well as on tested empirical or process-based models. A common set of input data and controlling processes will be analyzed and used in the assessment of both current and future potential carbon stocks, carbon storage, and GHG fluxes. Table 3.3 specifies the common characteristics and the differences between assessments of current and future potential carbon sequestration and GHG fluxes. In this section, methods and models supporting the assessment are introduced; specific technical information is discussed in more detail in the appendixes.

3.2.1. Framework for Assessing Current Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes

Relationship to Existing Inventory and Accounting Methods.—This methodology must be designed to maintain consistency with other existing (1) inventory and assessment guidelines and (2) methods for assessing current carbon stocks, carbon sequestration, and GHG fluxes. This concern involves both U.S. and international efforts developed under the IPCC guidance for land-use change and forestry (Penman and others, 2003; IPCC, 2006). The primary national-scale efforts in the United States include (1) the State of the Carbon Cycle Report (U.S. Climate Change Science Program, 2007); (2) the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. Environmental Protection Agency, 2009); (3) U.S. Department of Agriculture (USDA) Forest Service (2007), and (4) a report on the economics of sequestering carbon in the U.S. agricultural sector (Lewandrowski and others, 2004). These national assessments follow

Table 3.3. Time periods, land use and land cover, ecosystem disturbances, and land-management activities used for assessments of current and future potential carbon stocks, carbon sequestration, and greenhouse-gas fluxes.

[Abbreviations are as follows: LULC, land use and land cover; GHG, greenhouse gas]

Time period of assessment	LULC, ecosystem disturbances	Land management	Major input data and uses
Current assessment (2001–2010)	Current LULC, changes in LULC, and ecosystem disturbances	Current land management	In situ data, soil data, current climate data, and other input data together with current LULC and disturbances data are used to create empirical and process models to estimate current carbon stocks, carbon sequestration, and GHG fluxes.
Future potential assessment (2011–2050)	Projected future LULC and disturbances for each future scenario	Projected land management for each future scenario	Input data (above) combined with projections of climate, LULC, and disturbances to create parameters for simulation models and estimate future potential carbon stocks, carbon sequestration, and GHG fluxes.

the three-tiered approach recommended by IPCC (2006), as reviewed in chapter 2.

The primary methods and models used in this methodology for regional-scale assessment are a tier 3 effort in the IPCC (2006) hierarchy. Where appropriate data are unavailable, tier 2 approaches involving simple algorithms will be incorporated into the methodology. In addition, by assessing similarly defined ecosystems and pools and by using the same national-level datasets for land cover, vegetation, soils, and ecosystem disturbances that are maintained by the USDA, DOI, and other agencies, the methodology should yield consistent results at the national level. All of these approaches will maintain a relationship and consistency with other national efforts.

Carbon stocks, carbon sequestration, and GHG fluxes assessed for the period from 2001 through 2010 will be compared with those of other existing inventories. If conflicting results are found, efforts will be made to consult with appropriate agency programs, identify the source of discrepancies, capture and correct any errors, and notify the climate-change community about the differences.

Ecosystems and Current Land Use and Land Cover.—The ecosystem terms that have been chosen for this methodology and for the assessment of ecosystems are provided in section 3.1.2 and are described in table 3.1. To better represent carbon stocks, carbon storage, and GHG fluxes associated with LULC change, the national assessment will use a spatially explicit representation of the defined ecosystems and the thematic components or classes within each ecosystem, as listed in table 3.1. The NLCD 2001 land-cover classes can be easily aggregated and keyed to the ecosystems described in table 3.1; they also contain enough thematic classes that they can be aggregated to the six LULC categories used in IPCC (2006) for reporting purposes. The LULC classifications initially will be based on NLCD 2001 classes and will be modified to meet the needs of the project (table 3.4). Specifically, the following modifications will be made:

Forests.—The U.S. Forest Service Forest Inventory and Analysis (FIA) program defines forested land as "any plot that is 10 percent stocked, except woodland, can be forest if it's 5 percent stocked, with a minimum area of 1 acre [0.4 hectare] and width of 120 ft [37 m]" (Smith and others, 2009). The Multi-Resolution Land Characteristics Consortium (MRLC), which sponsors the development of the NLCD datasets, defines a forest class in the NLCD in terms of pixels with tree cover of greater than 20 percent. Differences in the definitions of "forest" can result in differences in forest biomass, especially in regions where woodland habitats (such as pinion-juniper and black spruce) are common. For forested areas, a solution by the MRLC, of which the Forest Service is a member, will be followed that uses remote-sensing-derived continuous forest-canopy estimates to interactively adjust spatial boundaries to match FIA in situ data (Huang and others, 2001; Hansen and others, 2003)

For forest cover in urban areas, the NLCD 2001 forest-canopy dataset that characterizes the percentage of forest canopy will be intersected with classes of developed lands in the NLCD 2001 land-cover dataset to provide regional (EPA Level II ecoregion) proportional distributions and averages of forest-canopy percentage in urban areas. The resulting urban forest cover will allow the biogeochemical model to quantify regional impacts of urban forestry on carbon stocks, carbon sequestration, and GHG fluxes.

Wetlands and Aquatic Habitats.—Wetlands include a variety of systems such as prairie potholes, coastal-plain woody swamps, boreal peat lands, and salt marshes (for example, palustrine habitats consistent with the U.S. Fish and Wildlife Service (FWS) definitions by Cowardin and others (1979)). Wetlands will be assessed using the same methods as for terrestrial ecosystems. Aquatic habitats in this assessment include coastal waters, estuaries, streams, rivers, lakes, impoundments, and other inland water bodies. Aquatic habitats will be assessed using models developed for this purpose. The boundaries for wetlands will be mapped by using NWI data that are supplemented with data about two NLCD wetland classes: woody wetland (class 90) and emergent herbaceous wetlands (class 95) (Homer and others, 2004). Aquatic habitats will be mapped by using a combination of datasets, including the National Wetland Inventory (NWI), the National Water Information System (NWIS) of the U.S. Geological Survey (USGS), the National Hydrography Dataset (NHD), the National Inventory of Dams (NID), digital line graphs (DLGs), and the NLCD. Open-water bodies such as rivers, lakes, and other aquatic systems will be similarly mapped. The initial land-cover map will be based on the revised NLCD 2001, as discussed above (table 3.4). To represent land-cover conditions for 2001 through 2010, the LANDFIRE ecosystem-disturbance data (Rollins, 2009) will be used along with a 2006 update to the 2001 NLCD by Xian and others (2009) to quantify contemporary LULC change. These data will inform a land-change model (section 3.3.2, "Land-Use and Land-Cover Change") that will be used to produce spatially explicit LULC maps for the period of 2001 through 2050. Reference datasets (such as LANDFIRE disturbance data) from the period of 2001 through 2010 will be used to calibrate and validate results of the LULC-change model for the same period of time.

Major current ecosystem disturbances caused by both natural and anthropogenic events (for example, wildland fires, forest cuts, insect and disease outbreaks, and storm damages) for 2001 through 2010 will be summarized by assessment units. Technical details for generating present LULC and ecosystem disturbances are provided in section 3.3 and in appendixes B and C.

3.2.2. Framework for Assessing Future Potential Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes

Scenario Framework.—Annual carbon stocks, carbon sequestration, and GHG fluxes for ecosystems of the United States will be analyzed within the context of a range of LULC and land-management projections (scenarios). The results will generate a rich set of spatial and temporal data products

Table 3.4. Thematic land-cover classes used to describe current conditions.

[The same classes will be used to parameterize modeling for future land-cover changes. Classes are modified from NLCD 2001 (National Land Cover Database; Homer and others, 2004). Abbreviations are as follows: m, meters; cm, centimeters]

Land-cover class	Description
Open water	All areas of open water.
Perennial ice/snow	All areas characterized by a perennial cover of ice and (or) snow
Developed	Includes NLCD 2001 developed classes with impervious surfaces accounting for more than 20 percent of total cover within a pixel.
Barren land	Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, unconsolidated shoreline, and other accumulations of earthen material.
Deciduous forest	Areas dominated by trees generally more than 5 m tall, and that represent more than 20 percent of total vegetative cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen forest	Areas dominated by trees generally more than 5 m tall, and that represent more than 20 percent of total vegetative cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
Mixed forest	Areas dominated by trees generally more than 5 m tall, and that represent more than 20 percent of total vegetative cover. Neither deciduous nor evergreen species are more than 75 percent of total tree cover.
Disturbed forest	Forest (deciduous, mixed, or evergreen) disturbed by logging. Forest areas that are thinned out, but not cleared, are not included in this category, but instead are tracked through management subattributes.
Dwarf scrub	Areas only in Alaska, dominated by shrubs less than 20 cm tall and where shrub canopy typically represents more than 20 percent of total vegetation. Dwarf scrub is often associated with grasses, sedges, herbs, and nonvascular vegetation.
Shrub/scrub	Areas dominated by shrubs less than 5 m tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.
Grassland/herbaceous	Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management, such as tilling, but can be used for grazing.
Sedge/herbaceous	Areas only in Alaska, dominated by sedges and forbs, generally greater than 80 percent of total vegetation. This sedge/herbaceous type can occur with other grasses or other grasslike plants and includes sedge tundra and sedge tussock tundra.
Lichens	Areas only in Alaska, dominated by fruticose or foliose lichens generally greater than 80 percent of total vegetation.
Moss	Areas only in Alaska, dominated by mosses, generally greater than 80 percent of total vegetation.
Pasture/hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.
Cultivated crops	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton; and perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land that is actively tilled.
Wetland	Includes all wetland classes currently mapped by NLCD.
Mining	Strip mines, gravel pits, and other surface materials or features resulting from mining extraction methods.
Irrigated land	Includes all irrigated cropland.

that will be used for assessing the effectiveness of mitigation activities to sequester carbon. Although scenarios will be constructed for assessment units, national-level consultation will be needed in order to establish construction guidelines for them that will ensure consistency across regional assessments. The use of a scenario framework will allow scientists to employ the methodology to provide a range of data products and bound overall uncertainties (fig. 3.3) of carbon stock capacity, carbon-sequestration capacity, and GHG fluxes.

Scenarios are neither predictions nor forecasts of the future; rather, they are ways of showing how the future may unfold under a set of assumptions. Scenarios are a useful tool for exploring the uncertainty associated with projecting potential resources in the future. Raskin (2005, p. 134) described scenarios as "drawing from the human imagination as well as science to provide an account of the flow of events leading to a vision of the future… using both words and numbers." He continued by stating (p. 134) that, "the great strength of scenario research lies in its blending of the richness, texture, and imaginative qualities of narrative with the structure, replicability, and rigor offered by modeling."

Scenarios combining both qualitative and quantitative elements have been used in several global assessments, including the Global Scenario Group (GSG) (Raskin and others, 1998), the World Water Commission scenarios (Alcamo and others, 2000; Cosgrove and Rijsberman, 2000), the IPCC "Special Report on Emission Scenarios" (SRES; Nakicenovic and others, 2000), the United Nations Environment Programme's (UNEP) third Global Environmental Outlook (UNEP, 2002), and the Millennium Ecosystem Assessment (Carpenter and others, eds., 2005). Within the global change community, an increased emphasis has been placed on integrated assessment scenarios that promote scaling from regional to global scales. One such effort was that of the UNEP third Global Environmental Outlook (UNEP, 2002) where, through a collaborative process, four GSG scenarios were refined with input from SRES and with an emphasis on giving the global scenarios a "regional texture" (Carpenter and others, eds., 2005). The use of similar scenarios as a methodology framework is proposed for the national assessment. The selection of the scenario framework should meet the following criteria:

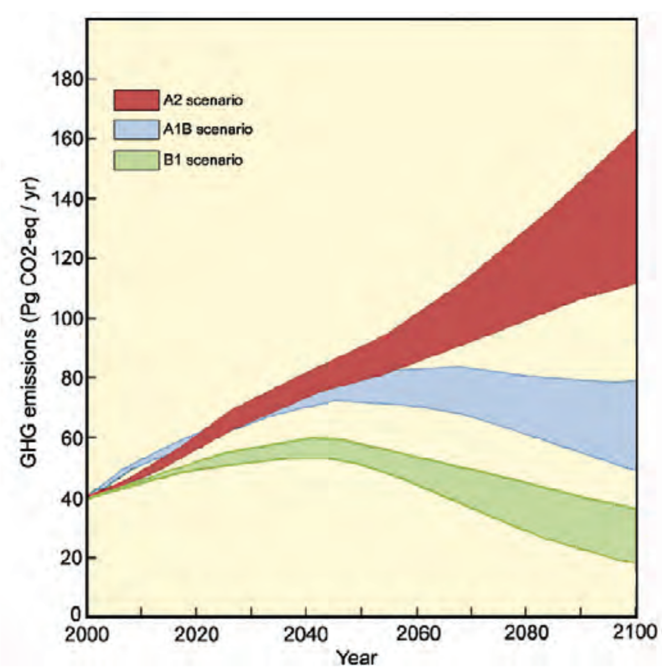

Figure 3.3. Graph showing hypothetical emission ranges for each of three scenarios defined by Nakicenovic and others (2000). The scenario framework will allow assessment of potential carbon sequestration capacities and associated uncertainties within each scenario and mitigation potential of GHG fluxes across the scenarios. Emissions are in petagrams of carbon dioxide equivalent per year ($PgCO_{2}$-eq/yr).

- Scenarios for the assessment should be based on socioeconomic conditions, such as trends in demographics, changes, and patterns of economic growth, and rates of energy consumption.—Socioeconomic scenarios, as opposed to climate scenarios, provide the means to explore the interaction of LULC change and the primary factors that drive that change, which ultimately affect the flux of GHG from ecosystems.
- The scenarios should consist of both qualitative and quantitative components.—(1) Qualitative components include "storylines," which describe elements of alternative futures. Storylines, or narratives, are scalable and can be interpreted to result in certain conditions based on regional landscape characteristics. Qualitative components also are highly useful for communicating scenario characteristics to a nonscientific audience, which is an important component of this research. (2) Quantitative components include modeling and projections of LULC and land management based on scenario assumptions about the interactions among the driving forces of change. Within the SRES process, there are 40 quantified scenarios based on 4 scenario families produced by 6 modeling teams (Nakicenovic and others, 2000).
- Links to associated projections of climate conditions.—These data are available from both the IPCC third assessment (IPCC, 2001) and fourth assessment (IPCC, 2007) reports and are based on the projections of emissions and changes in LULC associated with SRES scenario assumptions.
- Use of only current mitigation policies in order to provide a reference for the evaluation of potential mitigation activities.
- Scalability.—Data must be scalable from global down to regional scales. The chosen scenario framework must also be portable across regions (that is, the methods can be applied to different regions with consistent input parameters).
- Review by the scientific and policymaking communities.—For example, the SRES scenarios were produced

in an open process with broad scientific participation. Where possible, scenarios will incorporate robust projections of LULC drivers (for example, population projections) that are accepted by the scientific community.

- Transparency and easy communication to stakeholders and decisionmakers.—Scenarios should avoid depending on "black box" model outputs that cannot be modified or reproduced.

A set of regional LULC scenarios based on the IPCC SRES scenario structure (Nakicenovic and others, 2000) will satisfy the criteria listed above. A new set of scenarios, however, is being developed for the IPCC's fifth assessment (AR5) (Moss and others, 2010). The new process, representative concentration pathways (RCP), will begin with radiative forcing targets (measured in watts/m^2), and will allow modeling teams to explore various ways to achieve the forcing goal, including the imposition of various climate-change mitigation policies. Unlike SRES, which begins with a fixed set of socioeconomic conditions, the RCP process will provide a framework to allow modeling teams the ability to explore different and perhaps diverging LULC conditions to reach the same radiative forcing target. The first set of RCP scenarios already has been developed and analyzed (Wise and others, 2009); however, reference scenarios (those devoid of any climate-mitigation action) are still under development. Although the RCP approach is not the ideal framework for the reference scenarios for this methodology (see criteria above), they may provide insight for understanding the role of specific mitigation activities. As the RCP scenarios become more widely available, their use within the methodology framework will be considered, specifically to explore comprehensive climate-mitigation scenarios.

The IPCC SRES storylines (Nakicenovic and others, 2000) will serve as the primary basis of the framework for the assessment. Reference and mitigation (that is, enhanced for carbon sequestration) scenarios will be constructed for each of three major storylines found in the SRES. The storylines themselves are broad in scope, focus on global-level driving forces, and will need to be downscaled to the national and regional level for the United States. For this assessment, three IPCC SRES storylines from the IPCC Fourth Assessment (IPCC, 2007) will be used to guide the development of the specific LULC and management scenarios: A1B, A2, and B1 (Nakicenovic and others, 2000). The choice of three SRES storylines is dictated by the availability of the downscaled regional-climate data described in section 3.3 of this report. To date, the General Circulation Model (GCM) data for the B2 scenario that meet climate downscaling methods adopted for the methodology are not available. Should B2 climate data become available, or should an alternate source of climate data be found, then the B2 storyline may be included in the analysis.

For each assessment unit, regional LULC scenarios will be constructed based on experiences and results of ongoing LULC studies and regional expert knowledge. The SRES narratives and storylines and the existing knowledge of regional LULC changes provide a basis for constructing both the reference and mitigation scenarios, which will allow for opportunities to explore a wide range of regional LULC scenarios while remaining consistent with overall SRES assumptions.

Within each SRES storyline (Nakicenovic and others, 2000), there will be an opportunity to assess carbon stocks, carbon sequestration, and GHG fluxes under both a "reference" and an "enhanced" LULC and land-management scenarios. The framework will be designed to first identify a "reference" scenario of carbon stocks, carbon sequestration and GHG fluxes under the varied socioeconomic and climate conditions represented within the SRES storylines. Because the SRES storylines are inherently devoid of specific policies for sequestering carbon or mitigating GHGs, the use of reference assessments will provide a baseline against which effectiveness of various mitigation activities can be estimated. The "enhanced" scenarios will allow for both independent and joint evaluation of the LULC and land-management activities to enhance carbon sequestration and reduce GHG emissions within the assumptions of the IPCC SRES storylines.

The following sections introduce methods of constructing mitigation activities and scenarios that will be prioritized for the national assessment, evaluated within each assessment unit, and combined into the LULC and land-management scenarios. A summary of the reference and alternative scenarios also is provided. Further details are available in appendix A.

Mitigation Activities.—In the context of this assessment, mitigation activities refer to an ecological means of sequestering carbon or mitigating GHG gases (see table 3.5). The assessment includes two types of mitigation activities: land-management change (such as increased use of prescribed burning in the interior Western United States) and LULC change (for example, afforestation of agricultural land). See table 3.5 for candidate mitigation activities and chapter 2 for a more detailed description of current knowledge about these activities. Candidate mitigation activities will be presented to agencies that have land-management responsibilities and to other stakeholders for review and prioritization. The following criteria will be important for selecting mitigation activities to enhance carbon sequestration capacity:

- Sequestration capacity per hectare of mitigation-activity change
- Hectares of suitable lands for mitigation-activity change to identify applicable upper bounds on mitigation-activity change
- Time-effectiveness of sequestration to address how quickly the mitigation activity provides climate-change mitigation and duration of the effect of the mitigation activity on the sequestration rate (for example, five decades for management activities affecting forest and soil pools, one decade for cropland management changes, and two decades for LULC conversion)
- Permanence of sequestration to address differences in how much carbon remains sequestered over time for each mitigation activity

In addition to those criteria, the interests of consulting agencies and needs of policy makers will be considered in the prioritization of mitigation activities for the national assessment, but the final selection of activities will be subject to data availability, acceptance of assumptions, and (or) model capabilities.

Mitigation activities will be evaluated for their potential (the possible capacity in terms of amount and longevity) to sequester carbon and reduce GHG emissions in each assessment unit and to identify the effectiveness of these activities. For example, the conversion of grasslands to woodlands may not increase carbon-sequestration capacity in all regions. These evaluations will be conducted with an awareness of the tradeoffs within a management activity. For example, although reducing grazing may enhance carbon sequestration on rangelands, it also increases wildland fuel availability and flammability. The evaluation of mitigation activities for each assessment unit will be accomplished by (1) reviewing and synthesizing regional studies of carbon-sequestration mitigation activities, (2) estimating areas of land that are ecologically suitable and economically available for the mitigation activity, (3) consulting with regional experts (for example, participants in the “greenhouse gas reduction through agricultural carbon enhancement” network (GRACEnet) or the U.S. Fish and

Table 3.5. Candidate mitigation activities to be considered for the assessment.

[Abbreviations are as follows: CH_4, methane; N_2O, nitrous oxide; GHG, greenhouse gases]

Ecosystem	Strategy	Potential land-management change	Potential land-use or land-cover change
Forests	Carbon sequestration	Lengthen timber harvest-regeneration rotation Increase forest management intensity (increase in forest density, forest fertilization, thinning, reduction in fire fuel to reduce severe fires, management of insects and diseases)	Reduce logging frequency. Convert lands to forest (afforestation). Preserve forest, avoid deforestation.
	Mitigation of net GHG emissions	Reduce logging impacts	Reduce deforestation.
	Offsite wood product sequestration	Improve mill waste recovery Increase wood-product production Extend wood-product life Increase paper and wood recycling	
Croplands	Soil carbon sequestration	Reduce crop tillage Change crop mix to high-residue crops and crop rotations Increase winter cover crops Increase efficiency of crop fertilization Reduce summer fallow Restore agricultural land Use biochar	Convert to grassland and perennial crops.
	CH_4 and N_2O emission mitigation	Improve crop tillage Improve crop mix Increase efficiency of crop fertilization Expand irrigation	Reduce rice acreage.
Grassland/ shrublands	Soil carbon sequestration	Modify grazing management practices Improve efficiency of fertilizer Allow natural succession towards native shrub and forest Restore degraded rangelands	
	Mitigation of net GHG emissions	Reduce severe rangeland fire	Reduce conversion of grassland to energy-producing crops.
Wetlands	Carbon sequestration	Unknown	Restore wetlands.
	Mitigation of net GHG emissions	Unknown	Preserve wetlands.
Aquatic habitats	Mitigation of net GHG emissions	Reduce nutrient export from urban and agricultural lands Alter withdrawal from deep reservoirs	

Wildlife Service's (FWS) Landscape Conservation Cooperatives (LCCs)) for likely amounts and intensities of mitigation activities, and (4) developing a spreadsheet tool to quantitatively evaluate and summarize attributes of candidate mitigation activities. An evaluation of mitigation activities to enhance carbon sequestration (both the intensities and the amounts) will enable a more informed construction of alternative mitigation scenarios, which is pertinent to the limited number of scenario simulations that will be run. Refer to appendix A for more information on the methodologies used to evaluate mitigation activities.

Summary of LULC and Land-Management Scenarios.—A scenario is a combination of future potential LULC and land-management changes ("mitigation activities") associated with vetted climate and socioeconomic conditions. Scenarios will be used to help identify possible GHG mitigation activities under various assumptions. Figure 3.4 illustrates how one of the scenarios (A1B in Nakicenovic and others, 2000) will be used in the assessment framework and will be used to help illustrate the sections below. Appendix A provides the details of scenario development methods.

Reference Land Use, Land Cover, and Land Management (R).—The "reference land use, land cover, and land management" (R) scenario will be designed to provide reference LULC and land-management scenarios that are consistent with SRES storylines (Nakicenovic and others, 2000). Because of the use of SRES storylines in the methodology, the R scenario will be devoid of any direct carbon-sequestration or GHG mitigation policies or actions and thus serves as a baseline against which to compare alternative ecological carbon sequestration or GHG mitigation activities.

The first step toward creating a set of regional LULC and land-management scenarios will be to develop a set of national narratives that are consistent with the SRES storylines and the related three scenarios (Nakicenovic and others, 2000). This step will be done primarily through a national workshop. Using existing LULC projections associated with SRES storylines and other supporting data, expert opinions will be solicited in order to describe plausible pathways of LULC and land management based on the underlying assumptions of the SRES storylines. The "downscaled" national storylines will be viewed as geographically meaningful sets of SRES storylines with characteristics that are specific to LULC and land management in the United States. The primary outcome of the national workshop will be expanded LULC narratives and national-scale LULC trajectories. Nested within the national narratives will be assumptions about the regional variability of LULC and land management, where available. For example, a national-scale narrative might include assumptions on forest use while also highlighting certain regions as likely places for changes in forestry activities.

Regional reference scenarios will be based on the national scenarios discussed above. The foundations of regional scenarios will be LULC and land-management histories that will be developed through review of existing historical data sources and will include the comprehensive analysis of recent historical LULC change reported by the U.S. Geological Survey (USGS) Land Cover Trends project (Loveland and others, 2002). Consultations with regional experts will be used to project recent LULC into the future based on our understanding of the interactions among the drivers of LULC change. Regional experts will link both the SRES storylines and the national storylines with the biophysical and socioeconomic characteristics of the assessment units (ecoregions) in order to provide a range of LULC scenarios that will be consistent with recent historical observations.

The scenario construction process may incorporate exogenous projections of particular LULC types or management that are not covered by the SRES storylines. Examples may be projections of population from the U.S. Census Bureau or LULC projections from the U.S. Forest Service's RPA-mandated assessment. Maintaining fidelity to SRES storylines will be desirable, however, and the regional expert consultation process will determine the degree to which these exogenous projections will be used, if at all.

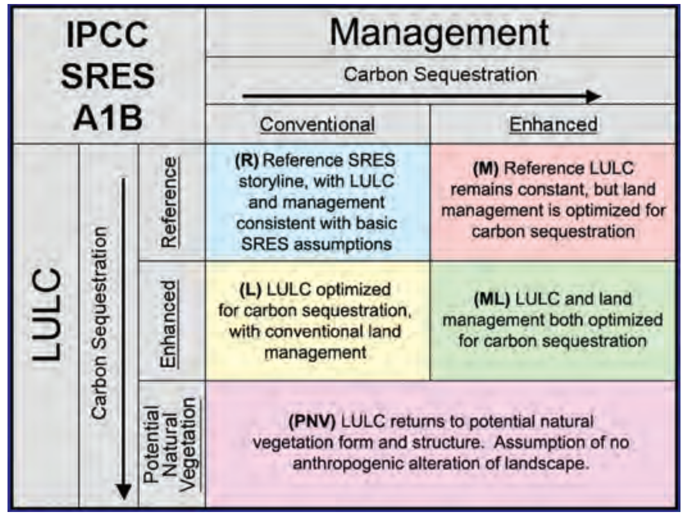

Figure 3.4. Diagram showing the assessment framework for each IPCC SRES storyline (Nakicenovic and others, 2000), using storyline A1B as an example. R represents the reference scenario with conventional (existing) land-management activities and will be used to generate spatially explicit land-use and land-cover forecasts for analyzing reference carbons stocks, carbon sequestration, and GHG fluxes. The enhanced land management (M), enhanced land use and land cover (L), or enhanced land use, land cover, and land management (ML) scenarios will be used to represent increases in carbon sequestration and (or) to mitigate GHG emissions. Future potential land-use and land-cover projections associated with the M, L, and ML scenarios will be produced in order to analyze how land-cover or land-management changes affect carbon stocks, carbon sequestration, and greenhouse gas fluxes. Finally, a potential natural vegetation (PNV) is introduced as a separate scenario. LULC, land use and land cover.

Reference Land Use and Land Cover With Enhanced Land Management (M).—The “reference land use and land cover with enhanced land management” (M) scenario will examine the potential for land-management activities to increase carbon sequestration and mitigate GHG emissions with land use unaltered from the reference conditions (that is, land use and land cover are unchanged). The M scenario will be constructed to enhance carbon sequestration by enhancing land-management activities (such as increased timber rotation age) from the reference point of the R scenario. Like the R scenario, the mitigation scenarios will be influenced by the national storyline in order to encourage regional experts to reflect beyond the current range of thinking and to create a diverse set of M scenarios. The national storyline will inspire different emphases on mitigation activities, different amounts of change, and different concerns for the temporal aspects of carbon sequestration, including timeliness and permanence of sequestration. The national consultation process will be relied upon to provide guidelines for mitigation scenarios, including setting realistic bounds on increases in mitigation activities. The aforementioned evaluations of mitigation activities at the ecoregion level are used to regionalize the M assessment. The result is an altered land-management prescription for the M assessment.

The modeling of the M scenario will be conducted using the same 2011 through 2050 LULC forecast data from the R scenario, but it will use the altered regional land-management prescription. The enhanced land-management prescription will be assessed using the ecosystem-level carbon and GHG modeling methods (discussed below in this chapter) to analyze the impacts of land-management change on carbon sequestration and mitigation of other GHG emissions.

Enhanced Land Use and Land Cover With Reference Land Management (L).—The “enhanced land use and land cover with reference land management” (L) scenario will examine the potential for land-use change to increase carbon sequestration and to mitigate GHG emissions but with land-management activities unchanged from the R scenario. The approach outlined in the section on the M scenario (above) will be used to inform construction of the L scenario. The SRES storylines will influence a range of LULC changes. For example, the emphasis of storyline A1B on managed solutions may be associated with evergreen plantations, whereas the emphasis of storyline B1 on more sustainable forestry may favor restoration of natural, unevenly aged forests. In addition, national programs for ecological carbon sequestration will be elicited from consulting agencies and applied to varying degrees (for example, high, medium, and low levels of national commitment) across the storylines. Maintaining the integrity of the SRES storylines (Nakicenovic and others, 2000) will become more difficult when land use is being altered because of the competing uses of the land for food, fiber, and energy; and the potential effects of large regional changes in agricultural or forest land use on potential displacement and leakage of carbon credits. Again, “reasonable” fluctuations in land-use proportions will maintain a general fidelity to the SRES storylines. The result will be an altered land-use prescription for the L assessment.

The modeling of the L scenario will be conducted by using the altered land-use prescription for a given SRES storyline and by using the LULC model to produce a spatially explicit LULC projection for 2001 through 2050. Without changing the land-management assumptions from the R scenario, an ecosystem biogeochemical method (discussed in section 3.3.4) will be used to analyze the impacts of the land-use changes in the L scenario on carbon sequestration and mitigation of other GHG emissions

Enhanced Land Use and Land Cover With Enhanced Land Management (ML).—The “enhanced land use and land cover with enhanced land management” (ML) scenario will examine the potential for both land-use, land-cover, and land-management changes to increase carbon sequestration and mitigate GHG emissions. Of all of the reference and enhanced assessment groups, the ML scenario will be designed to maximize carbon sequestration and GHG emissions mitigation, while staying within the context of the SRES storylines (Nakicenovic and others, 2000). Land-management activities related to enhanced carbon sequestration have been shown to be effective in significantly increasing landscape carbon stocks (Hudiburg and others, 2009). Methodologies for providing land-management and LULC prescriptions will be consistent with the M and L scenarios described above. The land-management activities of the M scenario will be distributed across the LULC data from the L scenario and used as input to the biogeochemical model. The resulting scenario will be used to analyze carbon sequestration and GHG-flux mitigation from land-use, land-cover, and land-management change.

Potential Natural Vegetation (PNV).—Potential natural vegetation is defined as the native vegetation that would grow on any given parcel of land given a set of environmental (climate and site) conditions, but without land-use or land-management practices. The potential natural vegetation (PNV) scenario will be designed to analyze each assessment unit’s carbon-sequestration potential in a scenario where the land is allowed to revert to the biophysical potential vegetation type, without anthropogenic alteration or management of the landscape, but with an approximation of present disturbance regimes (“current”). The use of PNV in the methodology will provide a basis for comparison with the other four scenarios (R, M, L, and ML). Given the persistence of urban and developed lands (that is, that a parcel of land rarely reverts to another land use once it is developed), the current urban and developed lands will be kept constant, but all other land-cover types will be allowed to revert to their potential vegetation types (native forests, shrub and grasslands). Therefore, the use of PNV as a scenario will have no LULC or land-management implications. Instead, it will be an exercise in modeling potential natural vegetation succession under overall influences of the biophysical environment as maintained by natural disturbances (Sundquist and others, 2009).

Development of potential natural vegetation will begin with a modeling of LANDFIRE’s biophysical settings (BPS) data layer. The BPS layer represents vegetation that may have been dominant on the landscape before European settlement and is based on both the current biophysical environment and an approximation of the historical disturbance regime (Dillon and others, 2005), a concept similar to that of the potential natural vegetation of Kuchler (1964). To bring the LANDFIRE BPS layer to "current" time, a vegetation succession-modeling tool will be used to model the biophysical potential of vegetation succession in the context of current and future climate and natural disturbances (disturbance modeling is discussed in detail in appendix C). The BPS map units will be aggregated to approximate the common NLCD classes that are used with the other LULC and land-management assessments (reference and enhanced). The translated maps will represent potential natural vegetation succession from 2010 to 2050, and they will be used to examine resultant carbon sequestration and changes in GHG flux for the PNV scenario.

3.2.3. Methodology Framework Summary

A comprehensive set of data products (table 3.6) will be produced for both the current and future potential assessment. The results of the assessment will provide opportunities to examine the implications of the EISA requirements (U.S. Congress, 2007) as described below:

- For a given assessment unit, ecosystem capacities for carbon stocks, carbon sequestration, and GHG fluxes will be reported by pools and flux types. For estimating the current carbon sequestration and GHG conditions, results will be averaged values for the years 2001 through 2010. Results will be constrained by available in situ data about carbon stocks, carbon sequestrations, and GHG fluxes, and will be supplemented by LULC change data, ecosystem disturbance data, and other biophysical data.
- For estimating the future potential carbon sequestration and GHG conditions from 2011 through 2050, regionally specific ecosystem capacities for increased carbon sequestration and GHG-flux mitigation will be estimated within each IPCC SRES scenario. The M, L, and ML scenarios (fig. 3.4) will provide information on the effects of specific land-use, land-cover, and land-management mitigation actions within a given assessment unit. This information also will inform the analyses of the most economically feasible regional mitigation actions.
- Regionally specific ecosystem capacities for increased carbon sequestration and GHG flux mitigation will be estimated in order to compare results across multiple SRES storylines (Nakicenovic and others, 2000). The variability in results across the SRES storylines will frame the uncertainties in carbon sequestration and GHG-flux mitigation that result from uncertain future demographic, socioeconomic, energy, and climate projections.
- The regionally significant effects on ecosystem services that will result from the potential increased carbon sequestration and mitigation activities will be identified. An analysis of such ancillary effects on ecosystem services can be conducted across different SRES storylines and climate projections, across different mitigation scenarios within an SRES storyline, across temporal projections, and across geographic landscapes.

Table 3.6. Summary of the assessment framework for linking climate-change mitigation scenarios to changes in ecosystem capacities for carbon stocks and carbon sequestration and to changes in greenhouse-gas fluxes.

[Covers current (2001–2010) and future potential (2011–2050) assessments. Abbreviations are as follows: SRES, Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change (Nakicenovich and others (2000); NA, not applicable; R, "Reference land use, land cover, and land management" scenario; M, "Reference land use and land cover with enhance land management" scenario; L, "Enhanced land use and land cover with reference land management" scenario; ML, "Enhanced land use and land cover with enhanced land management" scenario]

SRES storyline	Land use and land cover	Land management	Scenario code
		Current	
NA	Current	Current	Current
		Future potential	
A1B	Reference	Reference	A1B–R
		Enhanced	A1B–M
	Enhanced	Reference	A1B–L
		Enhanced	A1B–ML
	Potential natural vegetation	NA	A1B–PNV
A2	Reference	Reference	A2–R
		Enhanced	A2–M
	Enhanced	Reference	A2–L
		Enhanced	A2–ML
B1	Reference	Reference	B1–R
		Enhanced	B1–M
	Enhanced	Reference	B2–L
		Enhanced	B–ML
	Potential natural vegetation	NA	B1–PNV

3.3. Introduction to Assessment Methods

The scenarios and storylines described in the previous section outline an overall framework and describe data products that will be generated by the national assessment. Integrated assessment methods or models are required to assess current and future potential ecosystem conditions for carbon stocks, carbon sequestration, and GHG fluxes and produce the desired information products. In designing and developing the methods, choices were made based on technical merits, data availability, and the consensus of the underlying science for components of the assessment. The methods introduced here represent a hybrid methodology involving in situ and remote-sensing data, process-based ecosystem models, empirical models, statistical methods, and expert knowledge. The overall approach follows guidelines by the IPCC for agriculture, forestry, and other land uses in designing a combined tier 2 and tier 3 and approach 3 methodology (IPCC, 2006) to investigate LULC transitions, ecosystem disturbances, and changes in carbon stocks and GHG fluxes. Figure 3.5 illustrates relations and data flows among the major components of the methodology. The methods are briefly introduced in this section with detailed descriptions and discussions provided in appendixes A through I.

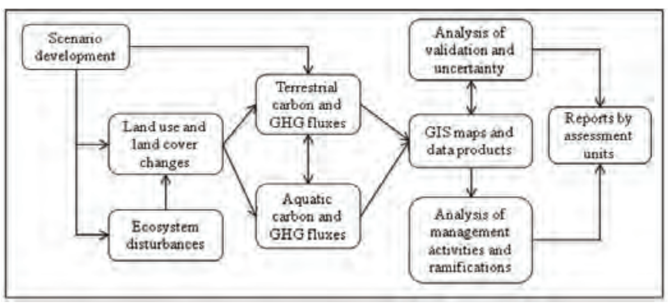

Figure 3.5. Diagram showing relations among major methods that are designed to run scenarios and produce assessment deliverables. These methods (statistical models, analyses, process models, or simple algorithms) are introduced in sections below. Abbreviations are as follows: GIS, geographic information system; GHG, greenhouse gas.

3.3.1. Technical Plan for Key National Datasets

Data Needs and Sources.—Various types of data will need to be assembled in order to complete a national assessment. The methodology will rely on existing data sets, promote collaborations to improve data availability, and use remotely sensed data to monitor key geospatial processes. Reference and observation data (in situ data, mapped biophysical data, remote-sensing data, and management- and policy-oriented data) will be used as the initial input data for (1) assessing present carbon stocks, carbon sequestration, and GHG fluxes, and (2) to parameterizing and constraining the methods and models that will be used for estimating future potential conditions. A critical deciding factor for the quality of the assessment will be the availability and quality of reference input data. Input data used for the national assessment will include the following:

- In situ, mapped, or remotely sensed (for example, light detection and ranging, or LIDAR) data about carbon stocks, rates of sequestration, or GHG fluxes in different pools and flux types
- In situ and remotely sensed data or studies that document the effects of controlling processes, such as ecosystem disturbances and land-use and land-cover change
- Up-to-date mapped biophysical data that has regional to national coverage, including current weather and climate, future climate projections, soil, permafrost, topography, land cover, vegetation types and structure, wetlands, and ecosystem disturbances (for example, areas affected by insect outbreaks, storms, and fires)
- In situ, mapped, or remotely sensed data that document temporally relevant ecological relations, such as information about the intra- and inter-annual variations for carbon stocks and GHG fluxes that can be measured in different pools and for different flux types, or information about the behavior of vegetation growth along different climate trajectories

A general summary of the assessment's input data needs, data sources and time span, essential attributes, and uses in the assessment methodology are provided in table 3.7.

Data Gaps and Plans.—The needs of the national assessment will not be met completely by existing data sources. Although some data development efforts may be necessary, the assessment largely will rely on existing suitable datasets for practical reasons. Other data gaps may be filled partially with surrogate data (for example, remote-sensing-based biomass data for ground biomass measurements); however, uncertainty caused by data gaps will be reported as part of the overall uncertainty assessment. Major data gaps are summarized below:

- A well-distributed, national spatiotemporal dataset of fluxes specifically for CH_4 and N_2O does not exist to support the national assessment and help constrain estimates of GHG modeling. Although the assessment will rely on all available flux data from sources such as FLUXNET, GRACEnet, and other available sources for parameterization and calibration purposes, the primary method for producing GHG-flux estimates for different ecosystems will rely on ecosystem simulation models (discussed in section 3.3.4). Uncertainties related to GHG-flux estimates will be provided at the regional scale. Data from other researchers or programs will be needed in order to increase the availability of GHG-flux data.
- The availability of many types of data, including data on GHG fluxes, is limited for Alaska; however, mapping efforts by the National Land Cover Database and the LANDIFRE database have improved the availability of data on land cover and vegetation as well as wildland fires. Forest, soil, and stream inventory data are undersampled and digital maps of vegeta-

Table 3.7. Data needs, sources, variables, spatial and temporal resolution, and uses in the assessment methodology.

[Datasets and sources represent only the major data needs. There are other data needs that are met by miscellaneous individual datasets that are not listed here. For explanations of acronyms, please see "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report. Abbreviations are as follows: CH_4, methane; CO_2, carbon dioxide; hr, hour; km, kilometer, m, meter; N_2O, nitrous oxide; yr, year]

Datasets and sources	Variables	Spatial and temporal attributes	Use in the assessment methodology
PRISM climate grid data, PRISM Climate Group, OSU	Precipitation, maximum and minimum temperature	4 km, monthly	Disturbance, aquatic methods.
NCEP, NOAA	Precipitation, temperature, humidity, wind speed, wind direction	32 km, 3 hr	Disturbance.
Downscaled IPCC GCM data: BCC–BCM2.0, CSIRO–Mk3.0, CSIRO–Mk3.5, INM–CM3.0, MIROC3.2.	Precipitation, maximum and minimum temperature	1 km, monthly	Disturbance, LULCC, terrestrial BGC methods.
EDNA and NED topographic data, USGS	Elevation, slope, aspect, stream networks and flows	30 m, static	LULCC, disturbance, aquatic and terrestrial BGC methods.
Soil databases: STATSGO2, SSURGO, USDA NRCS	Soil carbon and texture, crop suitability	250 m/1 km/polygon, static	Aquatic and terrestrial BGC methods.
Conservation datasets by USDA NRCS: CRP, WRP, CEAP, EQIP, CSP, WHIP, GRP, FRLPP, and HFRP	Acreage enrolled, locations, cost-sharing amounts, length of contract, crop or vegetation types	Parcel records, polygons, 1 to 30 yr	LULCC, terrestrial BGC methods, scenario development.
Litter and soil carbon turnover: literature compilations at national scale	Litter and soil carbon pool sizes (capacities) and their turnover times	250 m/1 km/polygon, dynamic	BGC methods; scenario development.
Agriculture residue management data, USDA NRCS	Tillage type and residue level information	County, biennial	LULCC, terrestrial BGC methods.
National Resource Inventory, USDA NRCS	Land use, agricultural and rangeland production	County, 5-yr cycle	Terrestrial BGC methods.
Areas of crop types, production, and management, USDA NASS	Tillage, crop rotation, crop harvest, grazing, manure application	County and state statistics, annual	LULCC, terrestrial BGC methods.
PAD-US (CBI)	Protected areas and status, level of protection, land ownership	County, decades	LULCC, disturbance.
FIA, U.S. Forest Service	Forest type, age class, biomass, and litter by pools, management information, disturbance information	Inventory plots, 5-yr cycle	LULCC, disturbance, terrestrial BGC methods, scenario development.
Urban Forestry Program, U.S. Forest Service	Urban forest coverage, production, disturbance	Subset of FIA plots	LULCC, terrestrial BGC methods.
Eddy-covariance flux-tower measurements from FLUXNET	CO_2 flux of various pools and ecosystems	Point, about 160 sites in the United States, hourly	Terrestrial BGC methods.
GRACEnet, USDA ARS	Chamber-based CO_2, CH_4, N_2O flux measures of agriculture soils, land-management scenarios	Point, 31 sites in lower 48 States	Terrestrial BGC methods, scenario development.
Carbon Cycle Sampling Network, NOAA	Atmosphere measurements of CO_2, CH_4, N_2O	Point data	Terrestrial and aquatic BGC methods.
National Atmospheric Deposition Program	Wet deposition of nitrate	Point, about 250 sites in the United States, weekly	Aquatic and terrestrial GHG methods.
National Water Information System, and National Water-Quality Assessment Program, USGS	Calculated constituent loads, POC, DIC, and DOC concentrations, other water-quality information	Variable	Aquatic and terrestrial BGC methods
Digital Coast dataset, Coastal Service Center, NOAA	Primary production in coastal waters and bathymetric details	About 130 estuaries, 30 m and 3-arc-sound	Aquatic methods.

Table 3.7. Data needs, sources, variables, spatial and temporal resolution, and uses in the assessment methodology.—Continued

Datasets and sources	Variables	Spatial and temporal attributes	Use in the assessment methodology
National Estuarine Eutrophication Assessment, NOAA	Nitrogen load, other chemical and physical parameters	About 130 estuaries, periodic (1992 to 1997)	Aquatic methods.
Watershed Boundary Dataset, USDA NRCS	Watershed boundaries, HUC	1:24,000 scale, static	Aquatic methods.
National Pollutant Discharge Elimination System, U.S. Environmental Protection Agency	Permitted waste discharges	800,000+ point sources, annual	Aquatic methods.
Storm data by National Hurricane Center, NOAA	Hurricane track archive and tornado track archive	Line segments	Disturbance.
Monitoring Trends in Burn Severity, U.S. Forest Service, USGS	Fire perimeters and severity classes (1984–present)	30 m, by fire event	Disturbance, terrestrial BGC methods.
National Fire Plan Operations and Reporting System, DOI	Fuel treatment types and locations	Point, yearly	Disturbance.
Forest Health Monitoring Program's Aerial Surveys, U.S. Forest Service	Insects and diseases, other disturbances	Variable sized, polygons, yearly	Disturbance.
LANDFIRE, U.S. Forest Service and USGS	Surface and canopy fuel classes, vegetation types, succession classes, transition pathways	30 m, updated annually	Disturbance.
Vegetation change tracker data products, USGS, U.S. Forest Service, NASA, UMD	Land-use and land-cover changes, and major ecosystem disturbances	30 m, annual products from 1985 to present	LULCC, disturbances, terrestrial and aquatic BGC methods.
National biomass and carbon dataset 2000, Woods Hole Research Center	Mapped aboveground biomass for conterminous United States, using 2000 space shuttle radar mission data	30 m, static	Terrestrial BGC methods.
MODIS, NASA	NDVI, FPAR, fire scars and fire perimeters	1 km, 8 and 16 days	Terrestrial BGC methods.
NLCD, USGS	Present and future LULC classes	60 m, 250 m, national maps	LULCC, disturbance, terrestrial BGC.
NWI, FWS	Geospatial wetlands digital data	GIS polygons	LULCC.
Distance to roads, National Overview Road Metrics, USGS	Distance to roads	60 m	LULCC.
U.S. Census Bureau, USDC	Population	County, decades	LULCC, disturbance.
National Irrigation Water Quality Program, DOI bureaus	National irrigation maps	1 km, 2001 and 2006	LULCC, terrestrial BGC methods.
Agricultural land-use costs, USDA ERS ARMS Program	Financial data about land use and commodity production	Tabular data	Tradeoff analysis of management activities.

tion structure, such as biomass, do not exist. Although this methodology will rely on surrogate data (for land cover, vegetation types, and fire data) and on limited data for soils and permafrost, the strategy for collecting data on vegetation, permafrost, and biomass will rely primarily on (1) increasing the spatial extent of LIDAR data and (2) conducting strategic sampling campaigns in areas where carbon-sequestration capacity and (or) GHG emissions are deemed most likely to change (see chapter 4 for a discussion of science needs).

- Assessment of carbon sequestration and GHG emissions in aquatic habitats will be based on existing data on streamflow, water chemistry, suspended sediment, coastal production, and sedimentation rates, which are stored in national databases such as the National Water Information System (NWIS) and the Reservoir Sedimentation Database (RESSED). Existing GHG data related to aquatic habitats also will be used, but the data are scattered (and are not in a central repository) and availability is limited. Additional data collection will be needed to improve the accuracy of the assessment; the following areas specifically will need to be addressed: (1) gaps in the spatial coverage of surface-water and groundwater chemistry (carbon and nutrient species); (2) a lack of fine-resolution temporal data for stream chemistry; and (3) poor spatial and temporal coverage for coastal, estuarine, lake, and impoundment sedimentation rates, sediment carbon concentrations, and GHG fluxes. It is recommended that additional chemical data be collected at sites along transects from mountains into coastal waters and at a temporal resolution sufficient to accurately estimate carbon, nitrogen, and suspended-sediment fluxes. The transport of carbon, nitrogen, and suspended sediments during storms can be particularly important, and estimating this transport will require a combination of manual sampling, automated sampling, and the use of in situ sensors. It is also recommended that measurements of sedimentation rate, organic carbon in sediment, and GHG fluxes in these aquatic habitats be substantially expanded, particularly in small impoundments, estuaries, and nearshore environments, where carbon cycling and burial can be quite rapid.
- Although the Soil Survey Geographic (SSURGO) database (http://soils.usda.gov/survey/geography/ssurgo) contains the most spatially detailed soil information available for the Nation (1:24,000- or 1:12,000-scale), it is not a periodic soil inventory and does not offer information on changes in soil carbon stocks. In addition, the SSURGO data are complete for approximately 86 percent of the land area of the conterminous United States and 7 percent of Alaska. Complete coverage for the conterminous United States and Alaska is available from the U.S. General Soil Map (STATSGO2, formerly STATSGO, http://soils.usda.gov/survey/geography/statsgo/), but it has a reduced spatial detail (1:250,000-scale for the conterminous United States and 1:1,000,000-scale for Alaska). The scale for Alaska is a concern because the region is undergoing warming trends (Chapin and others, 2008). Warming trends have lead to an increase in wildfires in Alaska that have the potential to release more CO_2 than all of the terrestrial net primary productivity (NPP) in the United States (Wiedinmyer and Neff, 2007; Chapin and others, 2008). Efforts are underway by the USDA NRCS to fill gaps in the SSURGO data, but workshops and studies that are targeted to address soil carbon dynamics are needed. An enhanced soil survey effort focused on soil carbon dynamics will make use of multiple data sources (for example databases with contributions by multiple investigators, satellite images, radar, LIDAR, digital elevation models, published soil maps and pedon datasets, targeted soil sampling, and opportunistic soil sampling in conjunction with trace-gas measurements) in order to improve the hydrologic, thermal, and landscape assessments of soil carbon and its potential for GHG release. The USGS has initiated the North American Carbon Network (Johnson and Harden, 2009), a database for Alaska with contributions from multiple investigators, and has begun to identify areas that are undersampled (Bliss and Maursetter, 2010). Soil carbon dynamics will be the topic for one or two targeted workshops with other relevant agencies and science programs. The results of the workshops can then be used to identify large and (or) vulnerable soil carbon stocks. A targeted soil-sampling campaign that links soil carbon stocks, soil carbon pools, and trace-gas characterization most likely will be recommended.
- Future potential climate scenarios associated with IPCC SRES storylines (Nakicenovic and others, 2000) are needed. Forecasts of future climate conditions have been produced using GCMs for each scenario and are available from the IPCC's and various other Web sites; however, downscaling the GCM datasets for use with the individual IPCC scenarios is a necessary step that will provide the spatial resolution required for the national assessment. Although downscaled datasets exist (for example, Maurer and others, 2007), they do not meet the data criteria of fine temporal resolution (monthly) for simulations, appropriate parameters (maximum and minimum temperature and precipitation), and fine spatial resolution (one to a few kilometers) for the three IPCC SRES emission scenarios of interest (A1B, A2, and B1). To generate these data, "change factors" (percent changes in precipitation and temperature between baseline and projected conditions; Arnell and Reynard, 1996; Pilling and Jones, 1999; Hay and Sem, 2000; Prudhomme and others, 2002; Arnell, 2003a,b; Eckhardt and Ulbrich, 2003; Diaz-Nieto and Wilby, 2004) will be computed by comparing the output from IPCC's Scenario 20C3M simulations for the 20^{th} century (IPCC, 2007), which uses GCM baseline conditions, with output for the three IPCC SRES emission sce-

narios (Nakicenovic and others, 2000). Five GCMs (see models in table 3.8.) from the World Climate Research Programme's Coupled Model Intercomparison Project (phase 3) (CMIP3) multimodel dataset archive will be processed; an ensemble means will be calculated and an assessment of ensemble ranges also will be performed for the three emission scenarios. These five models are the only ones in this collection that will provide data for both the current and future conditions needed for these scenarios. Ensembles of GCM output have been found to provide a more reliable representation of potential regional changes and uncertainties than the results from single models that cover large geographic extents (for example, Murphy and others, 2004; IPCC, 2007). Climate-projection output will be downscaled based on the geospatial relation of the change fields to historical PRISM data, which has 4-km spatial resolution (see PRISM Web site at http://www.prism.oregonstate.edu). Procedures for the estimating change fields and downscaling geospatial data are from an implementation developed by Lauren E. Hay and Steven L. Markstrom (U.S. Geological Survey, unpub. data, 2010). The resulting 4-km-resolution climate-projection data for monthly maximum and minimum temperatures and precipitation will be further downscaled to 1-km resolution through GIS interpolation to yield spatially smoothed climate data layers for use in conjunction with other fine-spatial-scale data layers for national assessment models (note that this second downscaling step provides no increase in quality over the input baseline PRISM data).

3.3.2. Land-Use and Land-Cover Change

Current Land Use and Land Cover.—The examination of carbon sequestration and emissions will require an analysis of changes in both land use (for example, a conversion of agricultural land to urban land) and land cover (for example, harvesting trees on forested land). To analyze both requires techniques that will use spatial and nonspatial data. The LULC method (this section) and the ecosystem disturbance method (section 3.3.3) will provide spatially explicit representations of both land-use and land-cover components, and will require spatially explicit input data. Given the need for a spatially explicit assessment for all areas of the Nation, remote-sensing data will be extensively used, from which we will determine land cover and will indirectly infer some land-use information. Data will be included on the broad land-use and land-cover categories that are readily available from remotely sensed data (land-use classes, such as "agriculture" and "development," or land-cover classes, such as "deciduous forest" and "barren"). Specific land-management activities associated with land use that aren't available as spatially explicit data will be handled through a statistical scaling approach that is related to the biogeochemical modeling framework. The integration of the LULC, ecosystem-disturbance, and biogeochemical models will provide the ability to examine the effects of both land-use and land-cover change on carbon sequestration and GHG emissions.

This section describes the procedures used to model spatially explicit LULC change. The NLCD 2001 database (Homer and others, 2004) will be used as the primary spatial-data source for land-cover information for the "current" time frame (2001), the year in which model simulations begin. The NLCD classification scheme has been modified to include not only NLCD land-cover classes, but also a limited number of land-use classes that could be handled easily by the LULC modeling framework (table 3.4). Augmentation of the NLCD dataset will be accomplished by incorporating (1) vegetation change tracker (VCT) data products (Huang and others, 2010) produced from the LANDFIRE program in order to map forested areas that have been disturbed by clearcutting, and (2) irrigated lands data (U.S. Geological Survey, 2010) to distinguish dry land from irrigated land. Given the complexity of modeling multiple urban-development classes at a national scale, we also have condensed the 2001 NLCD developed classes into one comprehensive developed class. See table 3.4 for the final modified thematic land-cover classes.

Future Potential Land-Use and Land-Cover Changes.— For each of the scenarios outlined in figure 3.4 and table 3.6, an LULC model will be used to provide spatially explicit thematic maps that cover each year from 2001 through 2050.

Table 3.8. General circulation models used to project future climate scenarios.

[Output from the five GCM models will be downscaled for this assessment. From Nakicenovic and others (2000). GCM, general circulation model]

GCM dataset name and abbreviation	Responsible agency
Bergen Climate Model 2.0 (BCC–BCM2.0)	Bjerknes Centre for Climate Research, University of Bergen, Norway.
Commonwealth Scientific and Industrial Research Organisation Mark 3 (CSIRO–Mk3.0)	Commonwealth Scientific and Industrial Research Organisation, Australia.
Commonwealth Scientific and Industrial Research Organisation Mark 3 (CSIRO–Mk3.5)	Commonwealth Scientific and Industrial Research Organisation, Australia.
Institute for Numerical Mathematics CM3 (INM–CM3.0)	Institute for Numerical Mathematics, Russian Academy of Science, Russia.
Model for Interdisciplinary Research on Climate 3.2 (MIROC3.2)	National Institute for Environmental Studies, Japan.

Between 2001 and 2010, LULC trajectories will be the same across all scenarios because they are considered collectively to be "current." The 2001 to 2010 time frame will be based on empirically measured LULC change as mapped by the 2006 NLCD change product (Xian and others, 2009) and the VCT data products (Huang and others, 2010) produced from LANDFIRE program. These data will serve as reference data to both calibrate the 2001 to 2010 "projections," and to validate model results. The LULC model will be used next to project LULC from 2011 to 2050 for each scenario.

The spatially explicit simulation model, "forecasting scenarios of land cover change" (FORE–SCE) (Sohl and others, 2007; Sohl and Sayler, 2008) will be used for projected LULC change. FORE–SCE uses two distinct, but linked, components called "Demand" and "Spatial Allocation," a structure that will allow for both linkages with external models and the inclusion of input data on driving-force variables derived from data at different scales. The complete LULC modeling framework will include an ability to ingest scenario-based assessments (LULC demand) to produce spatially explicit LULC maps that are compatible for assessing carbon sequestration and GHG fluxes.

The "Demand" component will provide overall proportions of LULC classes at a regional scale, and will be expressed as annual "prescriptions" for future LULC change. The annual prescriptions will be typically in the form of a simple table that will provide annual proportions of all mapped LULC classes. The "Demand" component will be constructed through extrapolation of historical trends, econometric modeling, integrated modeling, or scenarios based on expert knowledge. For this assessment, the LULC "Demand" component for the R scenario (see section 3.2.2) will be provided by the IPCC SRES scenario construction described in section 3.2.2 ("Framework for Assessing Future Potential Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes") and in appendix A ("Reference and Alternative Mitigation Scenarios"). The "Demand" component for the scenarios where LULC is enhanced for carbon sequestration (the M, L, and ML scenarios defined in section 3.2.2) will be done by combining the spreadsheet results (detailed in section 3.2.2 and appendix A) for enhancing LULC for carbon sequestration with the reference IPCC SRES scenario LULC proportions.

The "Spatial Allocation" component will use the LULC prescriptions from the "Demand" component to produce spatially explicit thematic LULC maps on an annual basis. The "Spatial Allocation" component of FORE–SCE was designed to take advantage of both historical and contemporary LULC research and data from the USGS. For this methodology, data from the USGS Land Cover Trends project (Loveland and others, 2002) and the NLCD (Homer and others, 2004) will be used to parameterize a unique, patch-based spatial-allocation procedure, one which can mimic realistic configurations and placement of individual patches of LULC change on an annual basis. The placement of patches will be guided by probability surfaces for each LULC type that are constructed through the analyses of empirical relationships between existing LULC patterns and a wide array of spatially explicit biophysical and socioeconomic data. The "Spatial Allocation" component places patches of LULC "change" on the landscape, one by one, until the annual prescription from the "Demand" component is met. The model then proceeds to the next yearly iteration, producing annual LULC maps from 2001 to 2050.

FORE–SCE also tracks the ages of forest stands. The initial (2001) age will be established by using the VCT data products (Huang and others, 2010) produced from the LANDFIRE program, which tracks natural and anthropogenic disturbances by analyzing historical layers of Landsat Thematic Mapper (TM) data and Forest Inventory and Analysis (FIA) sample points. A composite image will be constructed from these two sources that will identify the initial age of the forest stand for each 250-m pixel. The forest-stand age will be increased for each annual FORE–SCE scenario run; the age will be reestablished at "0" if forests are clearcut or if previously nonforested land is newly established (afforested) (for example, if a new pine plantation is established on previously nonforested land). Forest-stand age also will be used to more realistically mimic typical regional forest-cutting cycles and to inform biogeochemical modeling.

For the national assessment, each of the scenario runs outlined in figure 3.4 and table 3.6 will be run for each of the three IPCC SRES storylines (Nakicenovic and others 2000). The ecosystem-disturbance method (discussed in the next section) will be integrated directly with annual ecosystem disturbance data and with LULC data passed between FORE–SCE and the disturbance model in order to ensure that the projected LULC change results will be integrated with the annual ecosystem disturbance results (introduced in the next section). The direct integration of FORE–SCE, the disturbance model, and the biogeochemical modeling framework (the General Ensemble Modeling System, or GEMS) also will allow for the examination of land-use, land-cover, and land-management components that cannot be handled by any one individual model. Although FORE–SCE models all thematic LULC change for all terrestrial ecosystems, the model is not well equipped to handle coastal processes that affect thematic LULC change along coasts (for example, changes in coastal wetlands or other ecosystems due to sea-level rise or other coastal processes). An external coastal wetland model (discussed in appendix B, "Mapping and Modeling of Land-Use and Land-Cover Changes") will be used to map thematic LULC change for coastal wetland areas for each of the three IPCC SRES storylines (Nakicenovic and others, 2000). These data will be integrated with the FORE–SCE and disturbance model results when modeling is completed for a scenario. The final data products will be annual, 250-m-resolution, thematic LULC maps and transition statistics from 2001 to 2050 for each scenario. A much more detailed description of the LULC modeling framework can be found in appendix B.

Test Results Using the Land-Use and Land-Cover Model.—A test using the LULC modeling methodology was created for two EPA Level III ecoregions (modified from Omernik, 1987), the Mississippi Alluvial Plain (ecoregion 73) and the Mississippi Valley Loess Plains (ecoregion 74). Of the scenarios listed in table 3.6, LULC modeling was completed for the R and L scenarios (see section 3.2.2). Using a simplified protocol for regional scenario construction, annual prescriptions of LULC change that are consistent with the A1B scenario were produced for each ecoregion, thus providing the "Demand" component for the R scenario. The "Demand" component for A1B was fed to the FORE–SCE "Spatial Allocation" component, which was then parameterized independently for each ecoregion (using methods described in appendix B). Spatially explicit LULC maps from 2001 to 2050 then were produced for the R scenario.

The L scenario also was modeled. The spreadsheet approach for assessing land-use mitigation actions was used to independently identify optimal land-use changes that would increase carbon sequestration and mitigate other GHG fluxes in each ecoregion. Some selected land-use changes that resulted from running the L scenario were as follows:

- Restore forested wetlands (bottomland hardwood) where previously they have been used for agriculture in the Mississippi Alluvial Plain.
- Increase afforestation by converting marginal agricultural land to forests in the Mississippi Valley Loess Plains.
- Eliminate deforestation caused by processes other than forest harvesting and replanting.
- Eliminate the loss of wetlands (other than coastal wetlands) caused by conversion to other land uses.
- Increase the time between forest harvests from 25 to 45 years.
- Reduce the rates of clearcutting forests by 50 percent.

Annual LULC change prescriptions were constructed for the L scenario on the basis of the spreadsheet analysis and the land-use-mitigation actions identified above, thereby providing a "Demand" component. This "Demand" component was then fed into the FORE–SCE "Spatial Allocation" components, which was used to produce spatially explicit LULC maps from 2001 to 2050 for the L scenario.

Figure 3.6 shows the net LULC change between 2010 and 2050 for both the R and L scenarios, for the entirety of both EPA Level III ecoregions 73 and 74. Ecoregion 73 (the Mississippi Alluvial Plain) was characterized by very little LULC change in the R scenario, but it changed significantly in the L scenario (primarily due to restoration of croplands to woody wetlands). Ecoregion 74 (the Mississippi Valley Loess Plains) showed active LULC change in the R scenario due to significant urban development and afforestation (primarily by converting agricultural land to pine forests). In the L scenario, significantly more afforestation occurred, where more agricultural land was converted to natural forest types rather than pine forests. The L scenario also was characterized by much less forest cutting (the "anthropogenic" class in figure 3.6)

Figure 3.7 shows the initial 2010 LULC, and the projected LULC changes for the period 2010 through 2050 for a portion of the two ecoregions. The reference (R) scenario is used in parts *C* and *E* and the enhanced LULC (L) scenario is used in parts *D* and *F*. Very significant changes in LULC are evident between part *D* (the result of running the R scenario) and part *F* (the result of running the L scenario); the results project lower forest-cutting rates in the Mississippi Valley Loess Plains (Claiborne County, Miss.) and large increases in forested wetland restoration in the Mississippi Alluvial Plain (Tensas Parish, La.). The projected land-cover maps from 2010 to 2050 for both the R and L scenarios will be used to model carbon stocks, carbon sequestration, and GHG fluxes, as described in section 3.3.4.

3.3.3. Ecosystem Disturbances

As discussed in chapter 2, ecosystem disturbances are defined as episodic events that may affect the composition, structure, or function of an ecosystem (Pickett and White, 1985; E.A. Johnson and Miyanishi, 2001; M.G. Turner and others, 2001). Ecosystem disturbances are treated distinctly from global environmental change effects, which include sustained alterations in climate that may arise from increasing CO_2 in the atmosphere or nitrogen deposition (B.L. Turner and others, 1990). The definition of ecosystem disturbances is also separate from events related to LULC, such as forest converted to cropland. Major ecosystem disturbances are one of the primary mechanisms that have potential to reset carbon sequestration pathways and change ecosystems from carbon sinks to sources (Baldocchi, 2008; Running, 2008).

Disturbances Included in the Assessment.—Ecosystem disturbances are discrete events that affect the composition, structure, and (or) function of an ecosystem or landscape (Pickett and White, 1985; M.G. Turner and others, 2001; Johnson and Miyanishi, 2001). Ecosystem disturbances are important because they result in a transfer of carbon between live and dead pools; in the case of fires, the disturbance causes the immediate release of carbon and GHGs to the atmosphere (Campbell and others, 2007; Meigs and others, 2009). Carbon stocks, carbon sequestration, and GHG fluxes may be altered further in the years immediately following a disturbance because of patterns of mortality, regeneration, and productivity (Hicke and others, 2003; M.G. Turner and others, 2004). Currently, fuel treatments and controlled burning are used in many fire-prone ecosystems to reduce wildfire hazard and risk (Agee and Skinner, 2005). Recent studies also have demonstrated the potential reductions in carbon loss from fires in fire-prone ecosystems through the use of fuel treatments and controlled burning (Hurteau and North, 2009; Stephens and others 2009; Wiedinmyer and Hurteau, 2010); however, in ecosystems with long fire-return intervals, treatments may result in a reduction of long-term carbon-sequestration capacity (Harmon and others, 2009; Mitchell and others, 2009). Therefore, both ecosystem disturbances and disturbance-management activities must be incorporated in the assessment in order to evaluate their potential effects on carbon stock, carbon sequestration, and GHG fluxes.

The following ecosystem disturbance types (both natural and anthropogenic) should be considered in the national

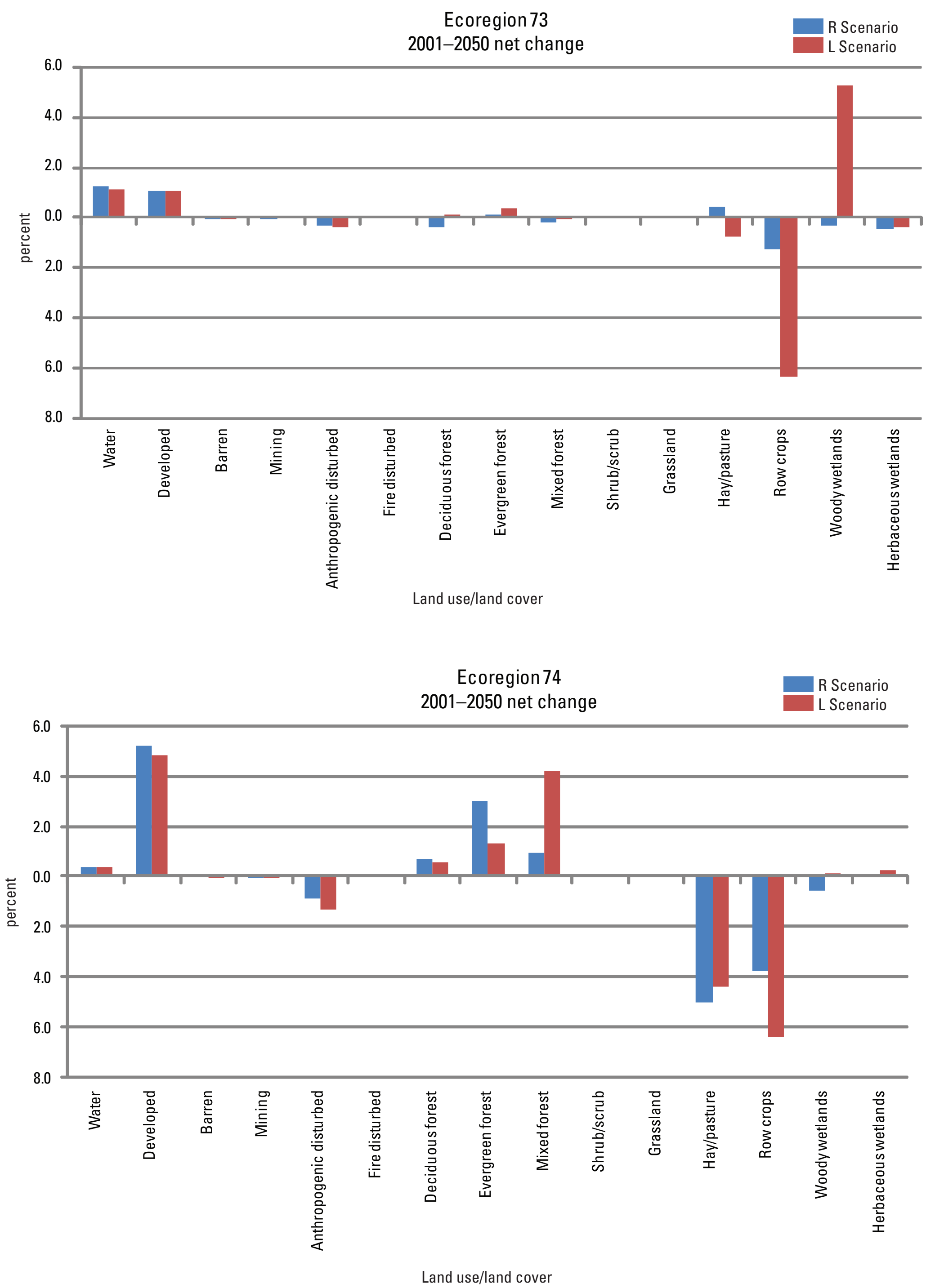

Figure 3.6. Graphs showing the net change for the modeled land-use and land-cover types in the two U.S. Environmental Protection Agency Level III ecoregions (modified from Omernik, 1987) used in the test study, using the prototype methodology and running both the R (reference land use, land cover, and land management) and L (enhanced land use and land cover with reference land management) scenarios. Ecosystem 73, Mississippi Alluvial Plain; Ecosystem 74, Mississippi Valley Loess Plains.

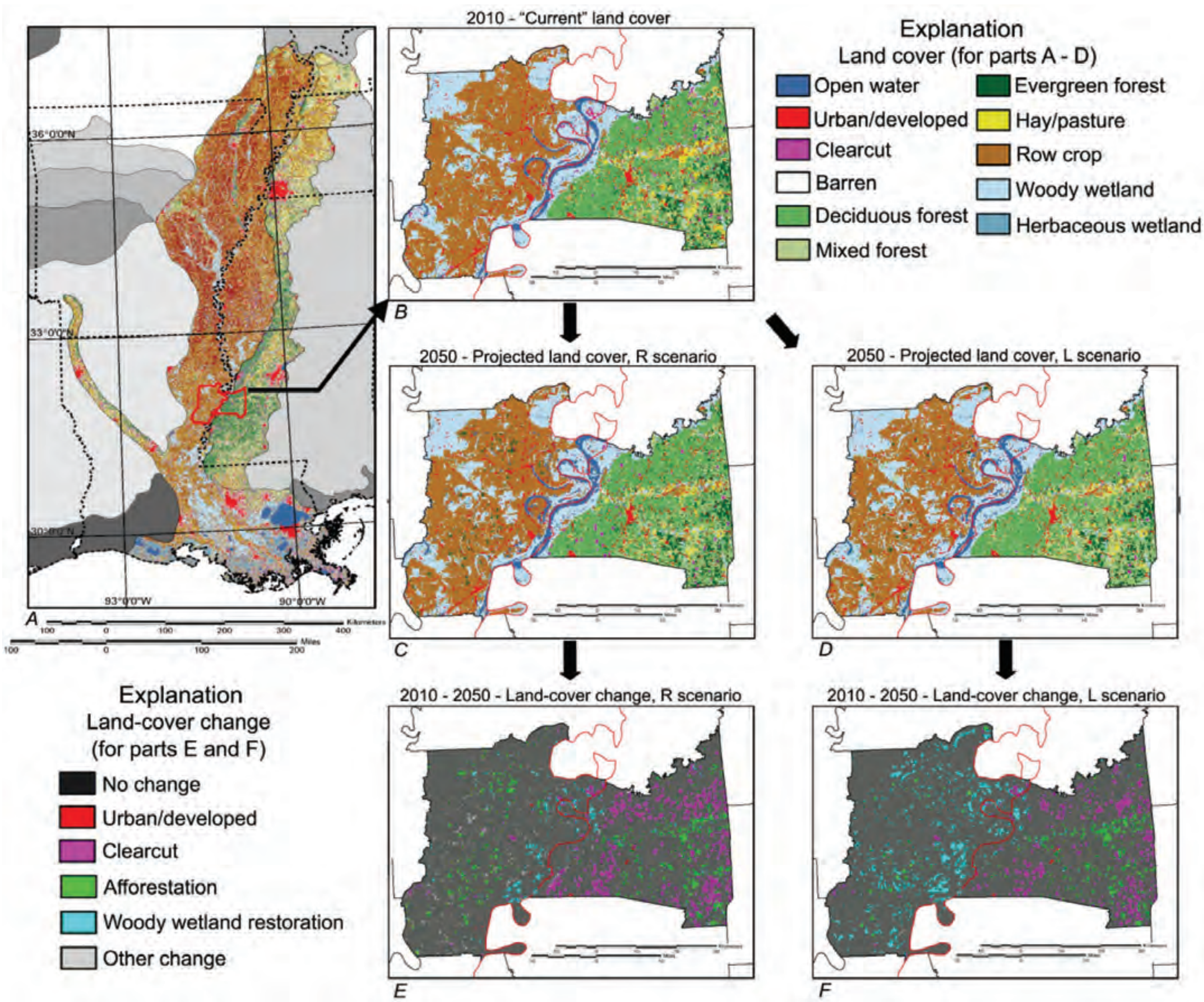

Figure 3.7. Maps showing the results of a land-use-modeling test for the A1B scenario (Nakicenovic and others, 2000). *A*, Area of study showing land-cover classes for two EPA Level III ecoregions (modified from Omernik (1987)) as follows: 1, Mississippi Alluvial Plain; 2, Mississippi Valley Loess Plains. Tensas Parish, La., and Claiborne County, Miss. (outlined on the map), were selected to run the scenarios that are shown in the enlargements (parts *B*–*F*). *B*, "Current" land cover (2010). *C*, Projected land cover in 2050 using the "reference land use, land cover, and land management" (R) scenario. *D*, Projected land cover in 2050 using the "enhanced land use and land cover with reference land management" (L) scenario. *E*, Land-cover change from 2010 through 2050 using the R scenario. *F*, Land-cover change using the L scenario. Obvious differences in land cover are evident in parts *E* and *F*.

assessment: wildfires, hurricanes, tornados and other damaging winds, insect- and disease-related forest mortality, and land-management activities such as fuel treatments and forest cuts (table 3.9). The impacts of disturbances and land-management activities on carbon stocks, carbon sequestration, and GHG fluxes will be considered for the following ecosystems: forests, grassland/shrublands, and wetlands.

Current Ecosystem Disturbances.—The task of capturing current ecosystem disturbances will start by creating annual summaries of past disturbances using records of recent wildfires, storms, and insect and disease outbreaks, by ecoregion. These annual summaries will include disturbance type, cause, number of events, and total area affected. Fire summaries also will include ecoregion-level estimates for emissions, which will be created by totaling individual estimates for each fire using the Consume model (Prichard and others, 2006) and the First Order Fire Effects Model (FOFEM) (Reinhardt and others 1997) with the fuel-loading model (FLM) and fuel-characteristic classification system (FCCS) data produced for the LANDFIRE project (Rollins, 2009). The annual disturbance summaries will be provided as tables and further summarized as probability distributions for each U.S. Environmental Protection Agency (EPA) Level II ecoregion.

Future Ecosystem Disturbances.—The occurrence and spread of disturbances are influenced by a variety of processes and patterns operating at different scales (Peters and others, 2004; Falk and others, 2007; Raffa and others, 2008). Therefore, the methodology to simulate future disturbances incorporates a series of components operating at different spatial and temporal scales to characterize and forecast regional patterns as well as the footprints and impacts of individual disturbance events. Relations between past disturbances (frequencies and extents) and climate, vegetation, and socioeconomic drivers will be identified at ecoregion scales using empirical relations, which also will be used to forecast potential future disturbance occurrence patterns. Future disturbance footprints will be simulated using a variety of approaches, described in more detail below and in appendix C.

Fire-related disturbances and fire-management activities will include wildfires, prescribed fires, and fuel treatments. The methods for forecasting wildfires will incorporate the four basic processes: ignition, spread, effects, and succession (Keane and others, 2004). The projections of ecoregion wildfire activity will be made using climate-driven predictions of the number of wildfires each year (Westerling and others, 2006; Preisler and Westerling, 2007). The individual ignition locations will be determined from empirical probability surfaces using climate, vegetation, land cover, and topography as predictor variables (Syphard and others, 2008). The predicted probability surfaces will be updated each year by incorporating changes made by the LULC (section 3.3.2) and BCG (section 3.3.4) methods. The spread of individual fires will be simulated each year using the minimum-travel time (MTT) algorithm (Finney, 2002), the LANDFIRE fuels and topography layers (Rollins, 2009), and National Oceanic and Atmospheric Administration (NOAA) North American Regional Reanalysis (NARR) weather data. Fuel-treatment projections (including prescribed fires) will be made from historical distributions (the number of treatments per year and the size of individual treatments). The treatment locations will be placed randomly within wildland vegetation types (forest, shrub, grass, depending on the type of treatment) in public lands and allowed to spread (using the MTT algorithm for prescribed fire and a “patch-grow” algorithm for other treatments; Finney, 2002) until a predetermined treatment area is reached or an entire patch of contiguous wildland vegetation has been treated.

Disturbances that are not related to fire (nonfire disturbances) will include insects and disease outbreaks, hurricanes, tornadoes, and damaging winds. The location and spread of insect and disease outbreaks will be based on empirical probability surfaces developed using epidemiology and species-distribution modeling techniques with vegetation, climate, topography, and previous outbreak locations as predictors (Elith and others, 2006; Phillips and others, 2006; Elith and Leathwick, 2009). Hurricane, tornado, and damaging wind activity (number of storms per year) will be based on a random selection of data from historical storm-occurrence summaries (for tornados and damaging winds) and national summaries (for hurricanes). An empirical storm-track generator (Vickery and others, 2000) will establish the storm path. For tornados and damaging winds, the footprint of the storm disturbances will be determined using remote sensing of landscape change (RSLC) techniques and historical storm locations. A similar

Table 3.9. Major natural and anthropogenic ecosystem disturbances, selected attributes, and data sources.

[MTBS, Monitoring Trends in Burn Severity project; LANDFIRE, Landscape Fire and Resource Management Planning Tools Project; RSLC, remote sensing of landscape change activities at U.S. Geological Survey; NFPORS, National Fire Plan Operations and Reporting Systems; USFS, U.S. Forest Service]

Disturbance type	Characteristic attributes of data sources	Data sources
Wildland fires	Fire size, severity, and emissions	MTBS, LANDFIRE.
Hurricanes, tornados, damaging winds	Storm tracks, severity, and areas of mortality	RSLC.
Insect and diseases	Areas of defoliation and mortality	USFS Forest Health Monitoring Program’s aerial surveys, RSLC.
Forest cuts (clearcuts and thinning)	Areas of cuts, cutting types	RSLC.
Fuel treatments (including prescribed fires)	Areas and types of treatment	NFPORS, LANDFIRE.

approach will be used for hurricanes, but a surface-wind-field and exposure model will also be incorporated to determine where damage to vegetation occurs (Boose and others 1994).

The redistribution of biomass among the different pools following both fire and nonfire disturbances will be quantified using a look-up table approach containing information on changes in biomass pools by ecosystem type, for each type of disturbance or management activity. The look-up table (example given in table D2 in appendix D) will be derived from published estimates and field inventories (for example, FIA) and will be used by the BGC modeling methods (discussed later in this chapter) to distribute biomass among different pools following disturbances. For fires, emissions will be estimated for each fire using data layers from the LANDFIRE fuel-loading model (FLM) and fuel-characteristic classification system (FCCS) with the Consume and First Order Fire Effects Model (FOFEM) fuel-consumption and emission models (Reinhardt and others, 1997; Prichard and others, 2006). The post-disturbance influence on vegetation productivity will be accounted for by the BGC methods.

During the disturbance simulations for the national assessment, a critical step will be to update the LULC and fuels data (fire behavior fuel model, canopy height, canopy cover, canopy bulk density, canopy base height, FLM and FCCS) that will be used to simulate disturbance locations and spread. During each annual time step in the simulation, in places where disturbances and management activities occurred, the LULC and fuels layers will be updated by using the existing vegetation state and transition models developed for LANDFIRE and “look-up” tables that link vegetation state to fuel layers and NLCD categories. Appendix C contains a detailed technical discussion of the data sources, the methods that will be used to characterize and model the ecosystem disturbances and management activities, and the data products that will be produced.

Disturbance modeling components are linked with the scenario framework (fig. 3.4). Climate changes associated with each of the IPCC SRES scenarios (Nakicenovic and others, 2000) will increase or decrease the frequency of the disturbances and will influence the spread and severity of individual disturbance events. LULC-change projections will interact with disturbance modeling by influencing the extent and arrangement of land-cover types within ecoregions, therefore constraining the spread of individual disturbance events. Additionally, the influence of disturbance-related land-management activities will be incorporated through fuel-treatment and fire-suppression modules. This integrated modeling framework will allow for a comparison of how changes in land cover, land use, and land management under different scenarios might influence disturbances and their impacts on carbon storage and GHG emissions in various ecosystems. See appendix C for more details on modeling major ecosystem disturbances.

Expected Outputs for Ecosystem Disturbances.—For the references and mitigation scenarios associated with the IPCC storylines (table 3.6), the final data products from the ecosystem disturbance modeling will include regional summaries and maps of current and future potential annual disturbances, levels of severity, and GHG emissions (carbon monoxide, carbon dioxide, methane, and nonmethane hydrocarbons). The data products will be presented as probability distributions that will summarize the range of results produced across replicated simulation runs.

Test Results Using the Ecosystem Disturbance Model.— The wildfire component of the ecosystem disturbance model was tested in the same two EPA level III ecoregions that were used in the test that used the land-use and land-cover model (section 3.3.2): the Mississippi Alluvial Plain and the Mississippi Valley Loess Plains. For the test, wildfire histories for the two selected ecoregions were constructed by using the Monitoring Trends in Burn Severity (MTBS) project database (Eidenshink and others, 2007). In order to show the relation between fire occurrences and the land cover (which is based on the nominal year 2001) in each ecoregion, only the data for wildfires that occurred before 2001 were used. This search resulted in data on 12 fires that occurred in the Mississippi Alluvial Plain ecoregion and 22 fires that occurred in the Mississippi Valley Loess Plains ecoregion. The small sample sizes prevented the construction of a predictive model that might demonstrate a statistically significant relation between wildfires and climate and LULC. Therefore, the number of wildfires simulated for each month was determined by drawing randomly from the historical distribution of monthly fire occurrences. A random distribution of ignition was used (with ignition points limited to natural vegetation types, such as is found in forests, grassland/shrublands, and wetlands) in order to estimate the probability of ignition locations.

Overall, the test showed that wildfires in the two ecoregions burned a small area; between 2001 and 2008, the observed (MTBS data) annual number of wildfires and area burned were 2 wildfires and 1,471 ha per year in the Mississippi Alluvial Plain and 0.5 wildfire and 166 ha per year in the Mississippi Valley Loess Plains. Simulation results for the same time period using the IPCC SRES A1B storyline (Nakicenovic and others, 2000) produced annual results of 0.6 wildfires and 2,450 ha burned in the Mississippi Alluvial Plain and 0.8 wildfires and 500 ha burned in the Mississippi Valley Loess Plains (figs. 3.8 and 3.9). The simulation results do not exactly match the observed results because of the stochastic nature of fire occurrence in the model; however, the simulated results were within the range of variability of observed values for number of fires and area burned each year. Because the wildfire simulation runs did not result in a large area burned each year in the test area, the fires’ effects were not incorporated into the BGC modeling methods discussed later in this chapter.

The initial results suggest that wildfires will not have a substantial impact on GHG emissions in the test region. The results indicate that there would be few fires and most of the fires would be small; less than 3,000 ha were burned each year in the simulations. Fuel consumption and emissions were not estimated using the FOFEM and Consume models because the input data (FCCS and FLM) were not yet available for the Southern United States (they are available now for Western United States). Predicting fire occurrence and spread is an

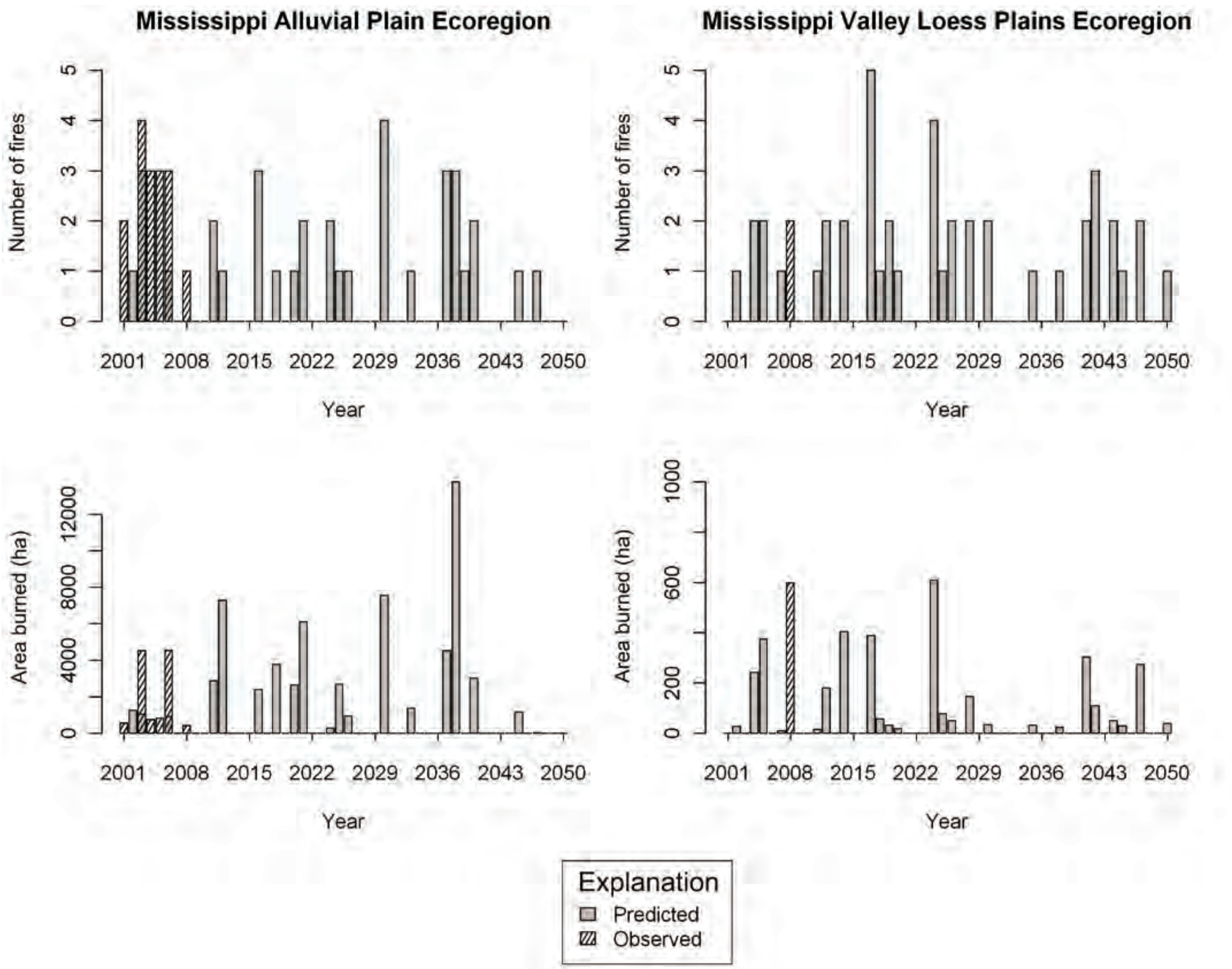

Figure 3.8. Graphs showing the observed and simulated number of wildfires per year, and the observed and simulated number of hectares of area burned by wildfire per year, using the IPCC SRES A1B storyline from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakicenovic and others, 2000) for the two EPA Level III ecoregions used in the test. Note that the horizontal axes for graphs showing number of hectares burned have different scales, and that some years had no observed or simulated fires.

inherently difficult process to simulate well. With this in mind, the differences between the observed and simulated number of fires and the area burned were not large; they were on a similar order of magnitude and reflected the inherently random nature of annual fire occurrence patterns and the spread of individual fires in the region.

3.3.4. Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes in Terrestrial Ecosystems

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) recognized two major approaches for estimating GHG fluxes in ecosystems: an inventory approach and a process-based modeling approach. The inventory approach (also referred to as the "bookkeeping" or "spreadsheet" approach) relies on direct measurements of carbon pools over a specific time period and applies empirically derived algorithms (such as carbon-response curves and emission factors) to estimate net carbon sequestration (Houghton and others, 1999). In contrast, the modeling approach uses process-based BGC models to estimate carbon stocks, carbon sequestration, and GHG fluxes over time in response to controlling factors such as climate, LULC change, and ecosystem disturbance. The carbon stocks, carbon sequestration, and GHG fluxes are estimated at each modeled time step. For this assessment, the current (2001–2010) and future (2011–2050)

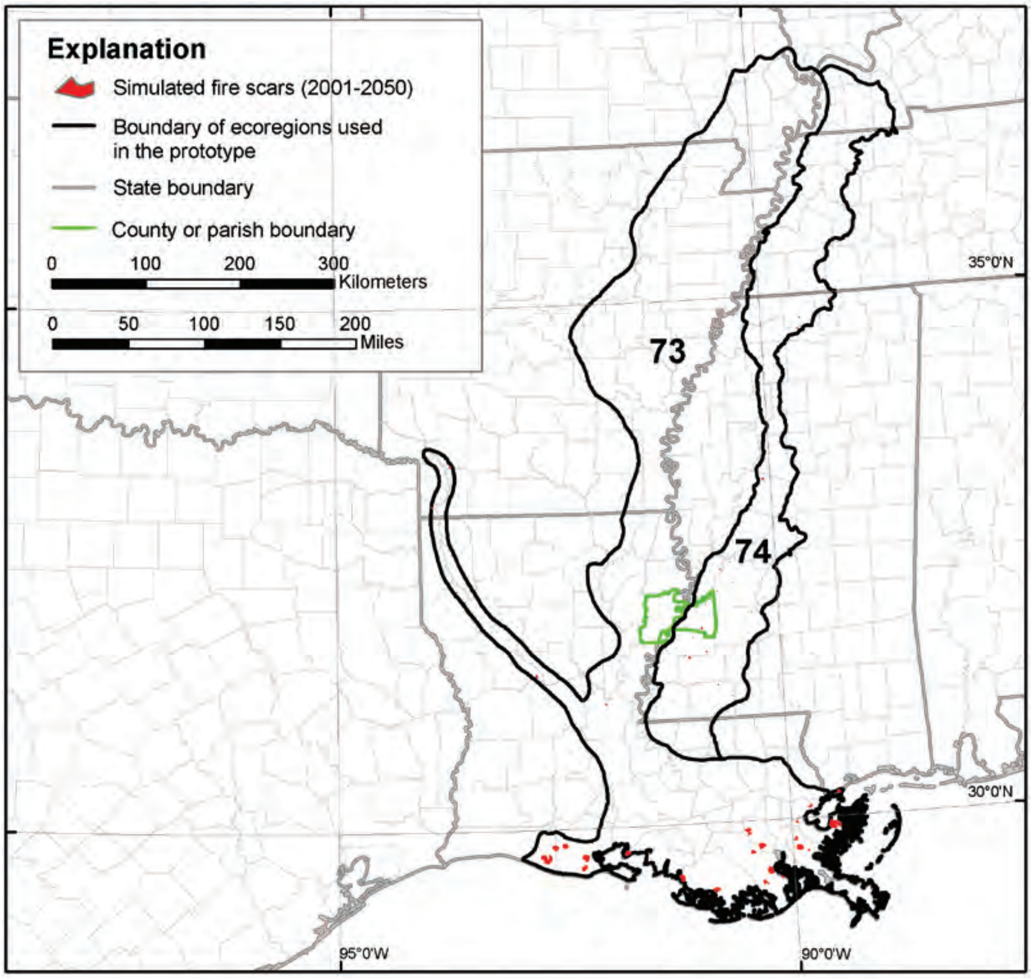

Figure 3.9 Map of the test area showing locations of simulated wildfires in two EPA Level III ecoregions for 2001 through 2050, using the A1B storyline from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (IPCC SRES; Nakicenovic and others, 2000. Ecoregions are as follows: 73, Mississippi Alluvial Plain; 74, Mississippi Valley Loess Plains.

carbon stocks, carbon sequestration, and GHG fluxes will be evaluated. For current estimates, the approaches will use field observations, published data, and other published information to calibrate model inputs and to evaluate model results. For future projections, the two general approaches will diverge on the basis of various LULC- and climate-change scenarios. In addition, the process-based modeling approach will incorporate several BGC simulation models for various ecosystems, as discussed below.

Accounting approach.—A spreadsheet model will be used to simulate carbon dynamics and GHG emissions. The spreadsheet approach generally will be limited to nonspatial or coarse-spatial-resolution simulations; the number of formulas used in a spreadsheet usually will be small, which will prevent the inclusion of a simulation of a complex ecosystem, GHG fluxes, LULC, or land-management interactions. The Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) provide equations and factors for building the spreadsheets. For this assessment, the spreadsheet will be developed in a parallel manner with the BGC modeling approach in order to compare and verify outputs (for example, there will be only a cursory check for sizes, distributions, patterns, or trends of estimates in order to capture and correct obvious errors).

Process-based modeling approach.—For this assessment, process-based BGC modeling will be conducted using the general ensemble modeling system (GEMS) developed by the USGS (S. Liu, Loveland, and Kurtz, 2004). The GEMS is designed to provide spatially explicit biogeochemical model simulations over large areas. The system uses both agent and direct implementation approaches to interact with encapsulated biogeochemical models, such as Century (Parton and others, 1987), Erosion-Deposition-Carbon Model (EDCM) (S. Liu and others, 2003), and Integrated Biosphere Simulator (IBIS) (Foley and others, 1996).

The agent implementation model interface is used with GEMS to conduct model runs of existing encapsulated BGC models. This approach requires minimum modifications to encapsulated models and can be useful for reusing models that are difficult to modify. Regional-scale BGC models, such as Century, EDCM, and IBIS, can be encapsulated or linked in GEMS (S. Liu, Kaire, and others, 2004; S. Liu, Loveland, and Kurtz, 2004; Tan and others, 2005; J. Liu and others, 2006). Because GEMS is designed to encapsulate multiple models and to parameterize and implement these models using the same data, it provides an ideal platform for using "model ensembles" to identify and address issues and uncertainty that are related to model structure and to mathematical representations of biophysical processes.

The direct implementation approach is used to merge BGC models directly with GEMS to allow more efficient, spatially explicit simulations. Many regional-scale model applications adopt a time-space sequence simulation approach, which implements a complete simulation for an individual pixel from beginning to end before moving to the next pixel. In an example linking GEMS with EDCM, a space-time sequence is used instead (each time step is simulated for the whole region before moving to the next step). This approach can be exploited to quantify lateral movements of water, soil, carbon, and nitrogen and can interface with other modeling systems such as FORE–SCE and ecosystem disturbance maps. BGC modeling will be a dynamic process, and national experts will be consulted during the assessment to provide comments on the overall modeling approach and to consider other potentially suitable BGC models for use on the GEMS platform.

As discussed above, there are two primary reasons to use both the spreadsheet approach and the process-based modeling approach for this assessment: First, the different methods each have their unique applications. The spreadsheet approach is relatively straightforward and transparent, but it is limited in spatial deployment and in linking with environmental changes and mitigation activities. In contrast, the process-based modeling approach is spatially explicit and dynamic, but it can be too complex for users to follow all of the processes considered and internal calculations. Second, applying both approaches provides the opportunity to crosscheck a model's performance and results and enhances overall confidence in assessment results.

Different input data will be used for the two different, yet complementary approaches because of the varying model structures and data-format requirements. For example, the combination of the GEMS spreadsheet and the EDCM uses joint frequency distribution (JFD) tables and Monte Carlo simulations for forest ages in order to generate the initial biomass in a forest; however, GEMS combined with Century uses remote-sensing data (showing tree-canopy cover types and height) to estimate biomass without considering the forest's age. The data-model integration will be improved to allow the same datasets to be used by different BGC methods during the assessment.

Table 3.10 lists examples of the methods or models, deliverables, technical processes, target ecosystems, and data needs or sources that will be used in the assessment. Details of the spreadsheet and process-based modeling methods are described in appendix D.

Assessment of Carbon Stocks and Carbon Sequestration.— The primary input data for the assessment of carbon stocks and sequestration will come from in situ measurements of aboveground biomass (inventory data), in situ soil measurements (for example, from GRACEnet), soil maps, carbon-flux measurements from eddy-covariance flux towers, remote sensing of vegetation, LULC maps, ecosystem-disturbance datasets, and land-management datasets available from various sources. See table 3.7 for the datasets and sources for this data. The assessment of carbon stocks and sequestration will be conducted by using both the spreadsheet and the process-based model simulation approaches. The net ecosystem carbon change will be calculated as the difference in the carbon stock between two time steps. As indicated in table 3.10, parameterization for current carbon stocks and sequestration will be based on observational data from different sources, as well as on current biophysical data such as soil, climate, LULC, and ecosystem disturbances. Parameterization for future potential carbon stocks and sequestration will require projected future potential climate, LULC changes, and disturbances along the scenario trajectories. The spreadsheet approach will compute carbon stocks, carbon sequestration, and GHG fluxes averaged at the level of assessment units, using predefined algorithms and the input data. For the process-based model simulation approach, carbon fluxes will be modeled using the technical processes listed in table 3.10. For both approaches, the primary drivers of carbon stocks and carbon sequestration will be climate change, LULC changes, ecosystem disturbances, and possible changes in land-management practices.

Assessment of Greenhouse-Gas Fluxes.—Modeling and assessing methane (CH_4) and nitrous oxide (N_2O) fluxes will be more complicated than modeling and assessing carbon dioxide (CO_2) fluxes because direct observational data for CH_4 and N_2O are scarce. Available data include eddy-covariance flux-tower data, field measurements from various sources and published literature, and soil-flux measurements that are compiled in sources such as GRACEnet. A general strategy for assessing GHG flux, in light of the shortage of measured flux data, will be to focus on ecological conditions such as soil moisture and temperature that control GHG fluxes, which are more prevalent and available.

The emission of CH_4 will be estimated through the simulation of soil biogeochemical processes, including methane production by methanogenic bacteria under anaerobic conditions, oxidation by methanotrophic bacteria under aerobic conditions, and transport to the atmosphere (Conrad, 1989). The principal controls on these processes are soil moisture, water-table position, soil temperature, the availability and quality of suitable substrates, and physical pathways for CH_4 to be released into the atmosphere. Many models have been developed to simulate site-scale processes of CH_4 generation, consumption, and transport (C. Li and others, 1992; Cao and others, 1996; Potter, 1997; Walter and others, 2001; Zhuang and others, 2006). Some of these models yield a detailed representation of the site-scale vertical soil processes; however, the deployment of these models over large areas has been challenging because of the difficulties in parameterizing these models and in simulating some of the critical driving variables, such as water-table position.

The denitrification-decomposition (DNDC) model (Li and others, 1992) has been applied to estimate CH_4 and N_2O fluxes for a range of ecosystems, including prairie potholes. Although DNDC is one option for estimating CH_4 and N_2O in this assessment, finding supporting data will be very difficult. A potential solution is to implement an approach that is

Table 3.10. Preliminary methods or models, quantifying parameters, technical processes, target ecosystems, and data needs or sources that will be used to assess parameters of carbon stocks, carbon sequestration, and greenhouse-gas flux.

[The methods or models listed have been tested and prototyped, but additional models may be added, depending on unique ecosystem conditions or technical needs encountered during the assessment. Input data requirements for each ecosystem also are listed. For an explanation of acronyms, please see "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report. Abbreviations are as follows: C_s, carbon stock; C_{sr}, carbon sequestration; GHG, greenhouse gas (greenhouse gas is carbon dioxide (CO_2), nitrous oxide (N_2O), and methane(CH_4)); C_{ed}, carbon erosion and deposition]

Method or model	Quantifying parameters	Technical process	Target ecosystem	Data needs or sources
Spreadsheet (Houghton and others, 1999)	C_s, C_{sr}, GHG flux	Algorithms based on storage-age growth curves	Forests Urban forests Grassland/shrublands Croplands Wetlands	Growth curve from FIA, crop production data from NRCS, NWI, local and IPCC standard GHG emission factors, GRACEnet data.
EDCM (S. Liu and others, 2003)	C_s, C_{sr}, GHG flux C_{ed}, carbon and nitrogen leaching	Maximum potential productivity, monthly time step, spatial sampling, and ensemble simulation Parameterizations (Cao and others, 1995; S. Liu, 1999; Parton and others, 2001)	Forests Urban forests Grasslands/shrublands Croplands Wetlands	LULCC data, current climate data, IPCC GCM projections, USDA agriculture production data, disturbance data (fire, drought), hydrological model inputs (soil erosion, deposition), land-management data (grazing intensity, fertilizer application), SSURGO soil data, GRACEnet data.
Century (Parton and others, 1987)	C_s, C_{sr}, GHG flux, carbon and nitrogen leaching	Maximum potential productivity, monthly time step, spatial sampling, and ensemble simulation	Forests Urban forests Grassland/shrublands Croplands	LULCC data, topography (DEM), current climate data, IPCC GCM projections, USDA agriculture production data, disturbance data (fire, drought), hydrological model inputs (soil erosion, deposition), GRACEnet data.
IBIS (Foley and others, 1996)	C_s, C_{sr}, CO_2, carbon and nitrogen leaching	Farquhar-type leaf level model, hourly time step, use of subpixel information.	Forests Urban forests Grassland/shrublands Croplands	LULCC data, topography (DEM), current climate data, IPCC GCM projections, USDA census data, disturbance data (fire, drought), hydrological model inputs (soil erosion, deposition).
USPED (Mitas and Mitasova, 1998)	C_{ed}	Empirical two-dimensional algorithm	Forests Scrub/shrub and grassland Croplands	Link with EDCM Soil erodibility factor (K) from SSURGO, SRTM data, LULCC data, precipitation data derived from climate data (current and future projections).
Zero-dimensional model	GHG flux	Process-based, simple framework, compatible with large scales Parameterizations (C. Li and others, 1992; Cao and others, 1996; Potter, 1997; Walter and others 2001; Hénault and others, 2005; Zhuang and others, 2006)	Wetlands	Link with EDCM NWI, SSURGO, NCDC, NLCD, regional wetland databases, GRACEnet data.

similar to an empirical approach developed by Cao and others (1996), which balances the needs of considering the site-scale processes with the feasibility of deploying the site-scale model over large areas in order to address spatial heterogeneity

Other methods also exist for simulating N_2O emissions (for example, C. Li and others, 1992; S. Liu and others, 1999; Parton and others, 2001; Hénault and others, 2005). Methods for estimating N_2O emissions from ecosystems will parallel those used by a study of N_2O emissions in the Atlantic zone of Costa Rica using GEMS and EDCM (S. Liu and others, 1999; Reiners and others, 2002). Nitrification and denitrification are the major processes that lead to the emission of N_2O from soils. Atmospheric and terrestrial deposition, plant uptake, mineralization, soil sorption, and soil leaching act as major controls on the nitrogen balance. For the assessment, the GEMS and EDCM algorithms will be enhanced in order to simulate the N_2O flux. The results of the simulation will be compared with observational data (for example, from GRACEnet).

Land Use and Land Cover Changes.—LULC change (such as a conversion of agricultural land to forest) is a significant driver of changes in carbon stocks, carbon sequestration, and GHG fluxes. For this assessment, the BGC modeling process using the GEMS platform will be directly coupled with LULC-change modeling results (section 3.2.2) to account for the effects of past and (or) current LULC changes and for projected future land-use changes on carbon-nitrogen dynamics in ecosystems. LULC-change maps generated by FORE–SCE model will be used to produce spatial simulation units. For an individual simulation unit, a LULC-change file, called the “event schedule file,” will be created. This file specifies the type and timing of any LULC-change event, as well as the type and timing of land-management practices, such as cultivation and fertilization.

Ecosystem Disturbance.—The extent and severity of natural or anthropogenic disturbances will be determined using combined outputs from LULC-change and ecosystem-disturbance methods. For example, maps showing fire perimeters and burn severity (Landscape Succession Model (LANDSUM) and MTBS maps (Keane and others, 2007; Eidenshink and others, 2007)) will be used in combination with the new fire modeling effort in simulation model runs to indicate the timing, location, and severity level of fires. The effects of fires will be expressed as biomass consumption loss and mortality loss (see table D2 in appendix D). On the basis of the loss rates, simulation model runs will reallocate the aboveground-biomass and soil-carbon pools for each individual land pixel. Consumption loss results in direct carbon emission to the atmosphere, but mortality loss converts live biomass carbon to dead carbon pools. The disturbed ecosystem will start to regrow (through the vegetation recovery process) based on the new soil-nutrient pool and new leaf-area index calculated by the models. The calculation of other disturbance effects will follow a similar approach, but with different carbon transition coefficients among various pools. The regrowth processes that follow the disturbances will be calculated based on light and water availability, temperature, nutrient availability, plant competition, and other environmental conditions. Tree planting will be assumed to follow a clearcutting or a stand-replacement fire event if a forest plantation is indicated in the resulting land-cover map; otherwise, natural vegetation recovery will be assumed to occur.

Assessment of Land-Management Activities.—In addition to natural disturbances (for example, geological disasters, wildfires), human land-management activities play a critical role in carbon stocks, carbon sequestration, and GHG fluxes. For example, implementing conservation residue management can significantly mitigate carbon emissions from soils and can make a bigger difference than conventional tillage management. For the assessment, the following land-management activities will be evaluated:

- Conversions between LULC classes and crop rotation
- Land management practices, including—
    - Logging or forest thinning
    - Forest fertilization
    - Fuel treatment of forest and rangeland, including thinning, prescribed burns, and so on
    - Grazing intensity
    - Tillage practices coupled with residue input (such as conventional tillage, reduced tillage, and no-till practices)
    - Fertilization rate for and manure application on croplands
    - Irrigation of croplands and forests

The key algorithms that account for land-management activities (such as irrigation, fertilization, and residue return) will be embedded in the GEMS. Relevant data and other parameter inputs will be compiled from existing databases, as noted in table 3.7.

Assessment of Erosion and Deposition.—Soil erosion and deposition affect soil-profile evolution, the spatial redistribution of carbon and nutrients, and the dynamics of carbon and nitrogen in ecosystems (S. Liu and others, 2003; Lal and others, 2004). Soil erosion and deposition will be assessed using the Unit Stream Power Erosion and Deposition (USPED) model (Mitas and Mitasova, 1998) to quantify the impacts of soil erosion and deposition on soil-carbon loss, soil-profile evolution, onsite dynamics of carbon and nitrogen, and offsite transport of carbon and nitrogen on the landscape and into wetland environments and aquatic systems. Quantitative estimates of soil carbon erosion and deposition estimates will be compared with assessments of aquatic carbon stocks and sequestration described in following sections.

Wood-Product Carbon Pool.—Carbon sequestration in wood products, landfills, and other offsite storage areas can be significant in the accounting of terrestrial carbon sequestration capacity (Skog and Nicholson, 1998). The fate of harvested wood can be tracked by using a simple offline spreadsheet-accounting approach (for example, S. Liu and others, 2003), but it requires forest-based assessments of harvest rates (Manies and others, 2005). The USFS maintains accurate data and methods for tracking and estimating carbon in wood products (for example, see W.B. Smith and others, 2009). For the assessment, the USFS, the EPA, and others will be consulted to develop the appropriate algorithms to estimate wood-product carbon.

Data Assimilation.—A major source of uncertainty in the assessment is the scarcity of in situ and other observational data obtained at appropriate spatial and temporal scales. Data assimilation refers to techniques that constrain simulations with reference conditions using limited observational data. For example, the Markov Chain Monte Carlo (MCMC) method (an algorithm used to simulate probability distributions) relies heavily on computation and is, therefore, difficult to apply over a region where the number of simulation units is large; however, the method can be an effective and ideal way to derive representative values and their uncertainties for the model parameters from limited point observations, such as data from FLUXNET. Other data-assimilation techniques include model inversion; for example, PEST (EPA's model-independent parameter estimation application; http://www.epa.gov/ceampubl/tools/pest/) (S. Liu and others, 2008), Ensemble Kalman Filter (EnKF) (Evensen, 1994, 2003), and Smoothed Ensemble Kalman Filter (SEnKF) (Chen and others, 2006, 2008). These methods have been implemented in the GEMS to derive parameter information for the model from plot measurements of carbon and nitrogen stocks (for example, S. Liu and others, 2008) and from eddy-covariance flux-tower observations (for example, Chen and others, 2008). For the assessment, a combination of data-assimilation techniques will be used to ensure that the model simulations agree well with various observations from different sources and scales.

Integration With Other Methods or Models for the Assessment.—Model integration will be a critical step for the assessment because of the time- and space-dependent relations among the different technical components. For example, modeling LULC requires information about site-scale soil fertility or soil organic carbon from BGC modeling to inform the allocations of crops in space and time. On the other hand, the ecosystem-disturbance information will affect land-use behaviors, such as timber harvesting. Without stepwise coupling between FORE–SCE and the ecosystem-disturbance model, timber-harvesting activities might still be prescribed in areas where biomass will have been completely consumed by fire in the ecosystem-disturbances model. Carbon or biomass stock (fuel load) will strongly affect the probability of fire occurrence and the level of severity of those fires, which requires coupling the ecosystem-disturbance model with carbon-stock information from the GEMS.

One goal of the GEMS modeling is to link the terrestrial and aquatic components of both the biogeochemical cycling and the transport of carbon. This linkage will constrain terrestrial simulations of carbon loss with calculations of lateral carbon flux, aquatic carbon stocks, and aquatic GHG emissions determined from water flow, water chemistry, and lake- and reservoir-sedimentation data, as described in section 3.3.5.

Uncertainty in the Assessment.—All models are simplified representations of the real world; therefore, biases and uncertainties in model results are common phenomena. The overall approach for estimating uncertainty for the assessment is discussed in section 3.3.8. To reduce biases in modeling, the BGC models will be calibrated with in situ data. Uncertainties (random errors) related to assessment results, parameters, and model structure will be handled following the general IPCC (2006) guidance. Influencing factors considered in uncertainty evaluation (such as forest age and soil-carbon content) should have an uncertainty range, expressed as a probability distribution function (PDF) curve or stated in a probability look-up table, so that the IPCC error propagation equations can be applied to evaluate regional level uncertainty. In modeling carbon stocks, carbon sequestration, and GHG fluxes, uncertainty factors also may include forest and crop species, soil type, canopy density, logging location, burn severity, and agricultural management. The PDFs of model parameters will be derived by using data-assimilation techniques at eddy-covariance flux tower sites across the country. Opportunities for biogeochemical model comparisons will be sought.

Test Using Terrestrial Methods to Assess Carbon Stocks, Carbon Sequestration and Greenhouse-Gas Fluxes.—The test area for the LULC modeling effort included Tensas Parish, La., and Claiborne County, Miss., in the Mississippi Alluvial Plain and the Mississippi Valley Loess Plains (EPA Level III ecoregions 73 and 74, modified from Omernik, 1987), respectively (fig. 3.10). The reason for selecting these two jurisdictions was to cover three major ecosystem types (forests, croplands, and wetlands). As of 2001, Claiborne County was dominated by forests (73 percent, consisting of 47 percent deciduous, 6 percent evergreen, 9 percent mixed, and 11 percent anthropogenic disturbances), followed by wetlands (10 percent) and croplands (10 percent, including hay/pasture). Tensas Parish was mainly classified into croplands (54 percent), wetlands (33 percent), forests (3 percent), and other (10 percent).

Three methods (GEMS-spreadsheet, GEMS–Century, and GEMS–EDCM) were used for the test. As noted above, different input data were used by the methods. GEMS–Century used STATSGO and GEMS–EDCM used SSURGO for the initial soil data. To initialize the biomass carbon data and to show the general relation between vegetation height and biomass carbon, GEMS–Century used vegetation-height maps from the interagency LANDFIRE database, whereas GEMS–EDCM used forest-age maps from FORE–SCE (which were derived from the FIA) and a correlation between age and biomass (that is, forest growth curves). The percentage of area of specific crop types (found by running a Monte Carlo simulation) was initialized as follows: corn, 34 percent; cotton, 30 percent; soybeans, 12 percent; wheat, 10 percent; and others, 14 percent. GHG fluxes in wetlands were estimated by using the GEMS–EDCM method, based on the technical processes described in table

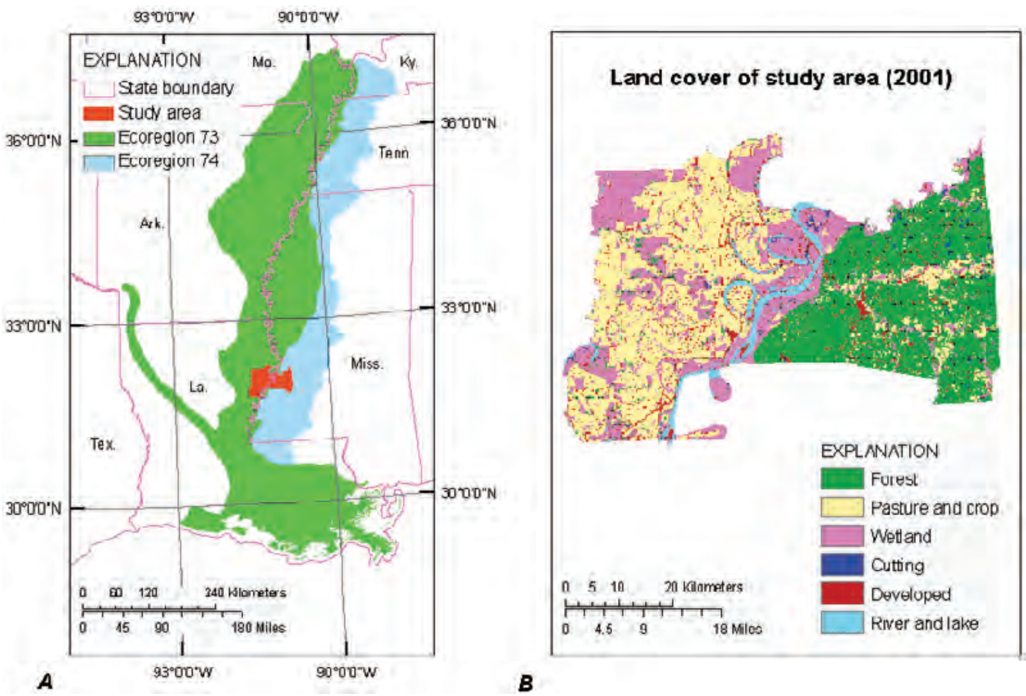

Figure 3.10. Map showing results of a test using terrestrial methods to assess carbon stocks, carbon sequestration and greenhouse-gas fluxes. *A*, Location of test area. *B*, Distribution of land-cover classes in 2001. The test area includes Tensas Parish, La., and Claiborne County, Miss., in the Mississippi Alluvial Plain and the Mississippi Valley Loess Plains (EPA Level III ecoregions 73 and 74 modified from Omernik (1987)), respectively.

3.10. USPED was used to estimate soil erosion and deposition. Monte Carlo simulation was applied to the initial forest ages, types of crops, and soil organic carbon. A complete ecoregion simulation was performed at a 250-m spatial resolution; every pixel was simulated only once instead of selecting sample pixels and performing ensemble simulations.

All simulations for the test were performed under the R and L scenarios (see definition above in section 3.2.2) generated by FORE–SCE for the period from 2001 through 2050 (see appendix B, "Mapping and Modeling of Land-Use and Land-Cover Changes" for a detailed discussion on mapping and modeling LULC changes). The model simulations were constrained by grain yields for crops and forest age growth curves. The major output variables included biomass carbon stock, total ecosystems carbon stock, carbon sequestration, and N_2O and CH_4 emissions. Additional output data, such as carbon stock and sequestration by pools, also were produced. No validation or uncertainty assessments (for both input data and data products) were performed for the test because of time constraints and because the validation and uncertainty assessments were designed to be conducted using the EPA Level II ecoregions (discussed below in this chapter), not the Level III regions used for the test.

Table 3.11 shows that estimates of the total carbon stocks at the beginning of the model simulations (2001) were 40.91, 34.22, and 43.30 Tg, and estimates for the end (2050) were 49.36, 51.89, and 48.07 Tg, respectively, for the GEMS-Spreadsheet, GEMS–Century, and GEMS–EDCM methods. For the initial carbon stock in 2001, the GEMS-Spreadsheet and GEMS–EDCM methods showed little difference, but the GEMS–Century method began with a much lower estimate (data not shown). The difference was caused by their different initialization approaches in biomass and soil organic carbon (SOC). Although the GEMS–Century method began with a lower carbon stock value in 2001, it reached a higher carbon stock value in 2050 than the other because of the higher carbon-sequestration rate during the study period.

Although there were differences in how the biomass carbon was initialized among these methods, some conclusions may be drawn from the test results (table 3.11, fig. 3.11). First, the annual rates of carbon sequestration were consistent, varying only within a range of 0.2 TgC/yr. Second, the GEMS–Century and GEMS–EDCM method runs demonstrated a synchronized temporal-change pattern, and the pattern was different from that of GEMS-spreadsheet method. This difference in temporal patterns may suggest that the two biogeochemical methods (GEMS–Century and GEMS–EDCM) captured the impacts of climate variability and change on carbon dynamics and the GCM-spreadsheet method did not. Third, carbon sequestration in biomass decreased over time primarily because of the aging of forests in the region.

The total carbon sequestration (the change in carbon stocks) using the GEMS–Century method was 17.67 Tg from 2001 to 2050, which was much higher than that calculated by using the GEMS-spreadsheet model (8.45 Tg) or the GEMS–EDCM method (4.76 Tg) (table 3.11). The corresponding annual carbon-sequestration rates for the test area were 0.17, 0.35, and 0.14 Tg C/yr from the GEMS-spreadsheet, GEMS–Century, and GEMS–EDCM methods, respectively. The differences shown here might be attributed to the differences in the input data sources, initial parameter values, and simulation algorithms of each model, especially between the GEMS–Century and GEMS–EDCM methods. For example, higher rate of carbon sequestration from the GEMS–Century

Table 3.11. Total carbon stocks and cumulative and additional carbon sequestration within the test area (Tensas Parish, La., and Claiborne County, Miss.), calculated using the specified method, and using the "reference land use, land cover, and land management" (R) and "enhanced land use and land cover with reference land management" (L) scenarios.

[Values represent the amount at the end of the given year. Abbreviations and acronyms are as follows: EDCM, Erosion-Deposition-Carbon Model; GEMS, general ensemble modeling system; Tg, teragrams]

Year	Total carbon stocks, by method, in Tg[1]			Cumulative carbon sequestration, by method, in Tg[1]			Additional carbon sequestration, by method, in Tg[2]		
	GEMS-spreadsheet	GEMS–Century	GEMS–EDCM	GEMS-spreadsheet	GEMS–Century	GEMS–EDCM	GEMS-spreadsheet	GEMS–Century	GEMS–EDCM
2001	40.91	34.22	43.30						
2010	43.45	38.37	42.56	2.54	4.15	-0.74	0.30	0.47	0.02
2020	45.57	42.11	43.71	4.67	7.90	0.41	0.52	0.54	0.15
2030	47.32	45.88	45.24	6.41	11.66	1.94	0.90	0.95	0.39
2040	48.48	49.14	46.70	7.58	14.92	3.39	1.27	1.43	0.82
2050	49.36	51.89	48.07	8.45	17.67	4.76	1.64	1.75	1.08

[1]Values were calculated using the "enhanced land use and land cover with reference land management" (L) scenario.

[2]Values represent the difference between the L scenario and the "reference land use, land cover, and land management" (R) scenarios.

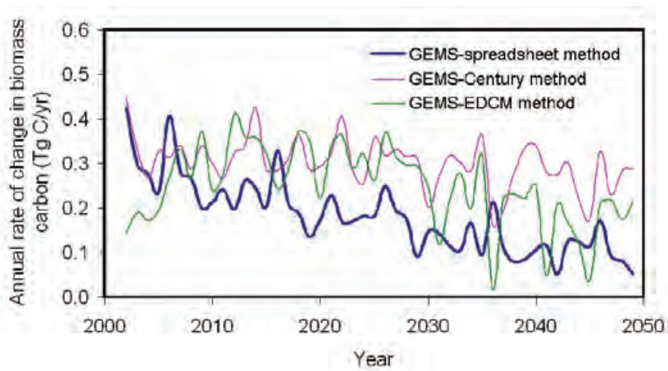

Figure 3.11. Graph showing comparisons of annual carbon-sequestration rates of biomass carbon stock among the three methods (GEMS-spreadsheet, GEMS–Century, and GEMS–EDCM) using the "enhanced land use and land cover with reference land management" (L) scenario for the whole test area from 2001 to 2050. The same comparison made using the same methods and the "reference land use, land cover, and land management" (R) scenario yielded similar results. Abbreviations and acronyms are as follows: EDCM, Erosion-Deposition-Carbon Model, GEMS, general ensemble modeling system; TgC/yr, teragrams of carbon per year.

method might have been caused by the lower initial biomass carbon values, faster biomass accumulation (compared to the GEMS-spreadsheet method's result), and SOC accumulation. In contrast, the lower carbon-sequestration estimate from the GEMS–EDCM method can be attributed to lower biomass accumulation (compared to the GEMS-spreadsheet method's result) and SOC loss.

All three methods estimated significantly higher ecosystem carbon stocks (table 3.11) for the L scenario, indicating additional carbon sequestration of 1.64, 1.75, and 1.08 Tg from the GEMS-spreadsheet, GEMS–Century, and GEMS–EDCM methods, respectively, relative to the R scenario. These amounts represented about an additional 20 percent, 10 percent, and 23 percent increase, respectively, above the carbon-sequestration values calculated using the R scenario. The result suggests that these models, rather consistently, are capable of quantifying additional carbon sequestration from enhanced changes in land-use and land-cover activities such as the Wetland Reserve Program.

Table 3.12 lists major differences in CH_4 and N_2O emissions between the GEMS-spreadsheet and GEMS–EDCM methods (no results are currently available from the GEMS–Century method). The major conclusions of this comparison of methods were as follows: (1) the GEMS-spreadsheet method estimated an annual CH_4-emission rate on wetlands that is more than double that of the GEMS–EDCM method; (2) estimates of N_2O emissions demonstrated opposite temporal trends, although both methods produced similar N_2O-emission rates; and (3) the GEMS-spreadsheet method showed small increases in annual emission rates of CH_4 and N_2O, whereas the GEMS–EDCM method showed decreasing trends. Both CH_4- and N_2O-emission rates were greatly affected by soil moisture, temperature, and substrate availability, and thus varied considerably depending on site conditions. For example, CH_4 emissions from rice paddies ranged from 2 to 1,642 kgC/ha/yr (Lindau and others, 1990). After reviewing many field studies, we found that the uncertainty of the CH_4 and N_2O emission factors using the GEMS-spreadsheet method was very high. The predicted emission rates of CH_4 and N_2O from the GEMS–EDCM method were within the uncertainty range of local field observations. Using the L scenario, the GEMS-spreadsheet method resulted in greater CH_4- and N_2O-emission rates than the GEMS–EDCM method (fig. 3.12) relative to the R scenario.

The preliminary results from the test highlighted several issues. First, the differences between the models (specifically the biases and errors in the individual models) were a major

Table 3.12. Annual emission rates of methane and nitrous oxide and their total differences (between 2001 and 2050), for the "reference land use, land cover, and land management" (R) and the "enhanced land use and land cover with reference land management" (L) scenarios.

[Abbreviations and acronyms are as follows: CH_4, methane; EDCM, Erosion-Deposition-Carbon Model; GEMS, general ensemble modeling system; L, "enhanced land use and land cover with reference land management" scenario; N_2O, nitrous oxide; R, "reference land use, land cover, and land management" scenario]

Year	CH_4 from wetlands (billion grams of carbon per year)				N_2O from all land (billion grams of carbon per year)			
	GEMS-spreadsheet method		GEMS–EDCM method		GEMS-spreadsheet method		GEMS–EDCM method	
	L	R	L	R	L	R	L	R
2001	28.47	28.42	15.50	15.47	2.74	2.74	2.77	2.76
2010	28.88	28.53	13.32	13.20	2.78	2.77	1.98	1.99
2020	29.26	28.36	12.66	12.45	2.82	2.76	1.91	1.92
2030	29.80	28.24	13.57	13.24	2.87	2.77	1.86	1.89
2040	30.43	28.10	13.04	13.65	2.92	2.77	1.74	1.77
2050	31.01	27.94	12.92	12.42	2.96	2.76	1.73	1.77
Difference between 2050 and 2001	2.54	-0.48	-2.59	-3.05	0.22	0.02	-1.04	-1.00
Average	29.64	28.27	13.50	13.41	2.85	2.76	2.00	2.02
Standard deviation	0.96	0.23	1.03	1.12	0.08	0.01	0.39	0.37

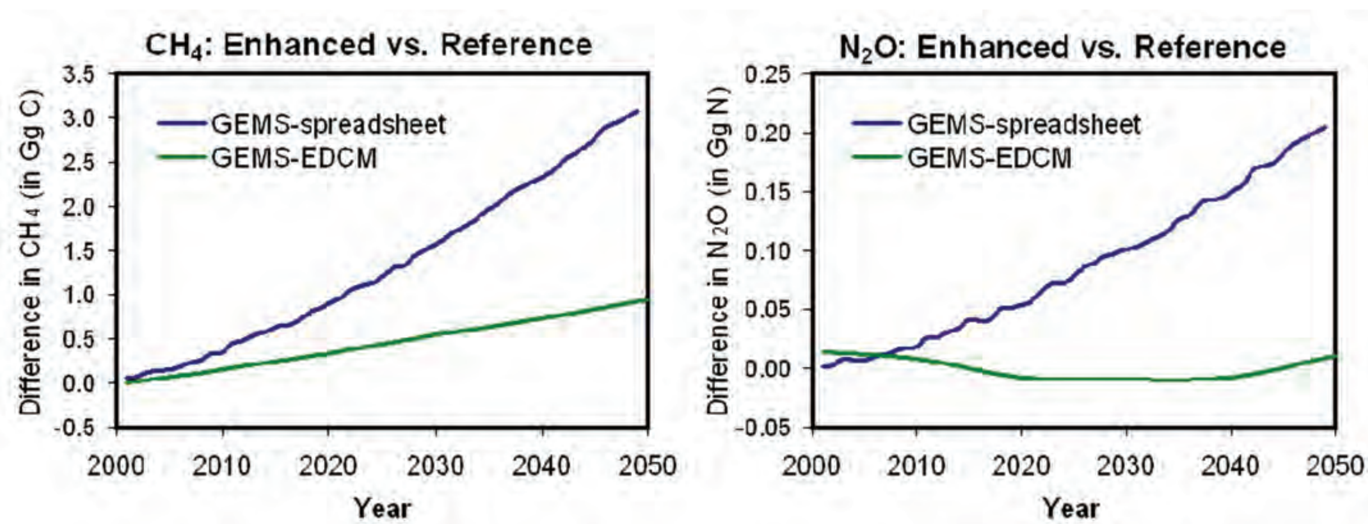

Figure 3.12. Graphs showing comparisons of annual methane emission from wetlands and the total nitrous-oxide emission from all land between the GEMS-spreadsheet model and the GEMS–EDCM model, showing the difference between the "reference land use, land cover, and land management" (R) scenario and the "enhanced land use and land cover with reference land management" (L) scenario, from 2001 to 2050. The emission rate from the GEMS–EDCM model is the 10-year average. Abbreviations and acronyms are as follows: CH_4, methane; EDCM, Erosion-Deposition-Carbon Model; Gg C, gigagrams of carbon; ; Gg N, gigagrams of nitrogen; GEMS, general ensemble modeling system; N_2O, nitrous oxide.

contribution to the overall uncertainty. Using model ensembles within the GEMS framework, some of the model uncertainty can be reduced and model's structure errors can be corrected. Second, the input data process (for example, using different forest biomass initialization data and processes in the models) might significantly affect the model's output and, therefore, the assessment of carbon stocks, carbon sequestration, and GHG fluxes. As new and improved data and modeling results become available, they will be incorporated into this methodology. Third, future efforts should emphasis literature review and metadata analysis in order to quantify the uncertainty of field observations at the regional scale.

3.3.5. Carbon Sequestration and Greenhouse-Gas Fluxes of Aquatic Ecosystems

Aquatic ecosystems in this assessment are defined to include streams, rivers, estuaries, coastal waters, and perennial ponds, lakes, and impoundments. Coastal and freshwater wetlands and ephemeral wet depressions that temporarily retain water following precipitation or flooding events will be assessed using the methods described for terrestrial ecosystems.

Inland aquatic ecosystems are important components of terrestrial landscapes and commonly are locations of intense carbon sequestration, biogeochemical cycling, and greenhouse-gas emissions (Cole and others, 2007). Similarly, coastal aquatic ecosystems are important because they receive, sequester, and biogeochemically process riverine and groundwater inputs of terrestrial carbon and nutrients. Coastal primary production is enhanced by inputs of terrestrially derived nutrients and coastal sequestration is enhanced by the co-transported sediments.

Aquatic ecosystems are not fully integrated into current terrestrial ecosystem models; therefore, their role in a national assessment of carbon sequestration and GHG fluxes must be quantified independently, relying more on empirical and statistically based assessment methods instead of the BGC modeling used for terrestrial ecosystems. This quantification requires the tracking of the carbon's sources and sinks from headwater areas, along stream and river courses, to and through inland water bodies, to and through estuaries, to its delivery and fate in coastal waters. Water is the principal carrier of dissolved and particulate carbon, and aquatic carbon flux is dependent on streamflow; therefore, a quantitative understanding of the relation between precipitation and runoff for ecoregions, and an accurate accounting of stream and river flow will be required. The assessment of the BGC cycling of aquatic carbon (including the production, consumption, and emission of GHGs) also will require additional knowledge of water chemistry and water's physical conditions, such as temperature, light penetration, and water-level fluctuations. The assessment of aquatic ecosystems will rely on empirical methods that use available national and regional datasets (current and forecasted) of streamflow, water chemistry, size and distribution of water bodies, watershed characteristics, sediment transport and deposition, and other environmental variables to estimate and predict amounts and rates of carbon sequestration and GHG fluxes. Appendix E provides detailed discussion of methods for assessing aquatic ecosystems.

Lateral Fluxes.—The initial assessment of lateral fluxes of dissolved and particulate carbon will be based on available streamflow and water-chemistry data, including data from the National Water Information System (NWIS; http://waterdata.usgs.gov/nwis). Long-term changes in lateral fluxes may be more closely linked to a change in water quantity than to a change in the relation between water and carbon yield (Striegl and others, 2007). Additionally, streamflow data are much more prevalent than water-chemistry data that specifically characterizes carbon yield, and predicting streamflow is much more reliable than predicting the change in carbon yield; therefore, the primary emphasis will be placed on developing an ecoregion-level understanding of the relation between water and carbon yield in water using existing data. Projecting the changes in water discharge based on climate-change and land-use change scenarios can then be accomplished using the USGS Precipitation-Runoff Modeling System[1] or similar programs.

These projections will be used together with empirically derived relations between water and carbon yield to project changes in lateral carbon export. Alternative methods for estimating lateral flux using data that characterize LULC in watersheds also will be explored, including the application of a carbon module (currently under development) of the "spatially referenced regressions on watershed attributes" (SPARROW) water-quality model.[2]. Existing SPARROW modules will be used to model nutrient and sediment fluxes (Alexander and others, 2008; Schwarz, 2008). A related goal of the assessment is to move towards fully coupling the GEMS and other terrestrial ecosystem models with a lateral export model. Additional information on the methodology for calculating carbon stocks, carbon sequestration, and GHG fluxes from inland waters, estuaries, and coastal waters is provided in appendix E.

Lakes and Impoundments.—The net storage of carbon in lakes and impoundments reflects a balance between carbon burial in sediments and GHG emissions from the surfaces and outlets of the water bodies. Carbon burial in lakes is driven mainly by autochthonous production, which has been quantified in a variety of settings (Cole and others, 2007). For the assessment, carbon-burial estimates will be compiled and analyzed statistically to derive a probability distribution function (PDF) of sedimentation rates in lakes. Carbon burial in impoundments (reservoirs and farm ponds) depends primarily on sedimentation rates and the concentration of the organic carbon in the buried sediments (S.V. Smith and others, 2005). Sedimentation-rate data are sparse, but include data for approximately 1,800 reservoirs in the Reservoir Sedimentation Database (RESSED);[3] these data will be used to develop a PDF of sedimentation rates in reservoirs. The concentration of organic carbon in the buried

[1]http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/software/oui_and_mms_s/prms.shtml.

[2]http://water.usgs.gov/nawqa/sparrow.

[3]http://ida.water.usgs.gov/ressed.

sediments often reflects the carbon content of the upland soils from which they were eroded (Ritchie 1989; S.V. Smith and others, 2005). For the assessment, the concentration of organic carbon in lake and impoundment sediments will be approximated on the basis of a new map showing soil carbon that was developed by the USGS using SSURGO data (Bliss and others, 2009). The surface areas of lakes and impoundments within each assessment unit will be mapped using data in the National Land Cover Database (NLCD). Carbon for each assessment unit will be calculated as the product of sedimentation rates, concentrations of organic carbon in the sediments, and the surface areas of lakes and impoundments.

Data on GHG emissions from lakes and impoundments are very sparse, particularly for CH_4 and N_2O; available data will be compiled from published literature, and the statistical distribution of GHG fluxes will be analyzed. The resulting PDFs will be combined with lake and impoundment surface-area data to estimate GHG fluxes from lakes and impoundments within each EPA Level II ecoregion. Region-specific data collection on sedimentation rates and GHG fluxes from lakes and impoundments will be necessary in order to further refine the model estimates; these data will enable the development of new regression models that will be used to estimate carbon sequestration in inland water bodies, using watershed characteristics and nutrient loads as explanatory variables.

Coastal Waters.—Coastal and estuarine biogeochemical processes related to fixation and burial of carbon are intimately tied to coastal autochthonous production through the process of terrestrial riverine transport of nutrients and sediments to estuarine and coastal environments. Nutrients transported from inland regions may stimulate the primary production in coastal waters (da Cunha and others, 2007; Seitzinger and Mayorga, 2008), and sediments may act to increase the flux of this material to the deep ocean, where the carbon would be buried and effectively sequestered from the atmosphere for millions of years (Hedges and Keil, 1995; Armstrong and others, 2002; Sarmiento and Gruber, 2002). The assessment of carbon sequestration in coastal waters thus will include a model of the primary production that is sensitive to the changing nutrient content of the water and a process model that explicitly incorporates both the primary production and the controlling processes in carbon remineralization, such as degradation during sinking, ballasting, bioturbation, and burial (Dunne and others, 2005). Because the method used here is a sensitivity analysis approach as a function of changes in terrestrial GHG transport, there is no need to spatially define the seaward boundaries of the coastal waters; however, because local conditions such as the water-column depth and the depositional environment are important controlling factors, the estimates of carbon sequestration and associated BGC processes will be produced on an individual basis for coastal waters that have a large terrestrial source and on a regional basis for coastal waters that have smaller sources. The changes in production and release of methane and nitrous oxide in sediments in intertidal, estuarine, and coastal waters will be estimated by using regression models to generate projected water-column depths, sediment production, and the contribution of groundwater to coastal waters, which can be significant (Bange, 2006; Hirota and others, 2007).

3.3.6. Analyses of Assessment Results—Mitigation Activities, Ecosystem Services, Costs, and Benefits

The primary data products of the assessment will contribute to an understanding of how carbon and GHG move in and out of natural and managed ecosystems under current and future potential conditions. The potentially broad range of users most likely will need data products that are synthesized to highlight (1) the potential effects (such as LULC change) and effectiveness of mitigation activities (such as land-management activities), (2) the direct and ancillary effects on ecosystem services, and (3) the associated economic and social costs for carbon sequestration and the reduction of GHG emissions. Quantifying the direct and ancillary effects on ecosystem services will increase the relevance to and impact of the assessment results on mitigation strategies and management actions. This section summarizes the proposed methods for analyzing the effects of mitigation activities, the effects on ecosystem services, and the relevant economic and social costs of mitigation activities. See appendixes D and F for details about the methods.

Analysis of the Effects of Mitigation Activities.—Converting nonforested land to forested land sequesters more carbon per unit of area (expressed as “carbon density”) than other land-management activities that are focused only on increasing the soil organic carbon (SOC) (Thomson and others, 2008). The actual amount of carbon stored in forest is a function of the forest type (for instance, deciduous or evergreen), its location, and the time required for the trees to grow. If the land use remains in agriculture, then increases in SOC will vary by management activity and the effects of crop cultivation are usually minimal after 15 to 20 years (West and Post, 2003). In addition, future climate conditions may dramatically alter key controls, such as temperature or moisture availability, thus causing the historic rates of carbon accumulation to be inaccurate. These variable effects of deliberate LULC changes or land-management changes on carbon sequestration can be evaluated quantitatively and displayed in formats such as table 3.13. For the assessment results, it is important to understand not only the total amount of potential carbon sequestration, but also the relations between the changes in carbon and the cost of gaining additional sequestration capacity. The cost may be expressed in terms of the time taken to reach the goal, resources that are spent, acres of lands used, and combinations of these. The effects of LULC changes and (or) land-management changes over a period of years can be easily analyzed using tools such as statistical software, GIS, or spreadsheets, and the results can be summarized using tables such as the example shown in table 3.13.

Analysis of the Effects of Mitigation Activities on Ecosystem Services.—Ecosystem services are the benefits that people and societies derive from the natural processes that sustain ecosystems (Daily, 1997). A mitigation strategy may have ancillary effects on ecosystem goods and services. Ancillary effects are defined as those effects that are subordinate to the primary goal or intended impact of a strategy, policy, or mitigation activity, including unintended consequences. Any change, either anthropogenic or naturally occurring, that affects structural components (such as the composition of a plant community) or processes (such as nutrient cycling) will impact the quality, quantity, and types of services produced from that ecosystem. Although it is beyond the scope of the assessment to quantify all ecosystem services, some of the important services that are likely to be affected by mitigation activities for ecological carbon sequestration are listed in table 3.14.

Estimating and forecasting the changes in carbon stocks, carbon sequestration, and GHG fluxes resulting from mitigation strategies will be based on the spreadsheet and the GEMS modeling approaches described in section 3.3.4 and appendix D. Many of these primary assessment data products can also be categorized as ecosystem services (table 3.14) including carbon stocks in soils and vegetation, carbon sequestration, CH_4 and N_2O emissions, net

Table 3.13. Example of a table format for reporting the effectiveness of mitigation activities for sequestering carbon, by the duration (years) of the implementation.

[Mitigation activities include land-use and land-cover changes and land-management activities. The values in the cells would be given as MgC/ha/yr (millions of grams of carbon per hectare per year). LULCC, land-use and land-cover change]

Mitigation activity	Duration, in MgC/ha/yr							
	0–5 years	6–10 years	11–15 years	16–20 years	21–25 years	26–30 years	31–35 years	36–40 years
LULCC								
Conversion of pasture to evergreen forest								
Conversion of croplands to woody wetland								
Land-management change								
Increased harvest rotation								
Increased conservation tillage								
LULCC and land-management change								
Conversion of pasture to managed evergreen forest								

Table 3.14. Ecosystem services that are likely to be affected by mitigation activities and will be analyzed, their functions, and the assessment data products that will be used to analyze the effects of mitigation activities.

[Abbreviations are as follows: CH_4, methane; GHG, greenhouses gas; N_2O, nitrous oxide]

Ecosystem service	Function of the ecosystem services	Assessment data products to be used in analyzing effects of mitigation activities
Soil formation	Supporting	Soil organic carbon.
Primary production	Supporting	Net ecosystem productivity.
GHG mitigation	Regulating	Soil organic carbon. Carbon sequestration. N_2O, CH_4 emissions.
Water quality	Regulating	Soil erosion. Nitrate retention.
Food	Provisioning	Grain production.
Wildlife habitat	Provisioning	Species richness. Occupancy and connectivity models. Species climate vulnerability. Metapopulation dynamics.
Fiber	Provisioning	Timber production.
Recreation	Cultural	Species richness. Occupancy models.

ecosystem productivity, timber production, grain production, and soil erosion. The estimates of how changes in carbon stocks, carbon sequestration, and GHG fluxes will affect ecosystem services will be produced for each ecoregion because they will be based on the primary assessment data products.

In addition to data already produced as the result of the analysis of mitigation effects for carbon stocks, carbon sequestration, and GHG fluxes, further analysis will be necessary. As an example, biophysical production functions and habitat suitability indices will need to be constructed based on the known relations between the LULC classes in an ecosystem (generated by FORE–SCE and GEMS modeling) and the relevant ecosystem services (Nelson and others, 2008; Tirpak and others, 2009). For example, suitable habitat for specific wildlife species will vary as a function of forest composition and will be different for evergreen and deciduous forests. These data will be combined with existing models such as SWAT (Soil and Water Assessment Tool of the USDA), GEMS–Century, GEMS–EDCM, and the Landscape Disturbance and Succession model (LANDIS–II, a forest landscape model created by a consortium of the USFS, University of Wisconsin, and Portland State University). A distributed geospatial model-sharing platform will be used to facilitate sharing and integrating these models, which will quantify ecosystem services and provide decision support. Additional details are provided in appendix F.

Given the need to have regionally specific information and our limited understanding of the complex relationships among ecosystem processes, land-management actions, climate change, and ecosystem services, this part of the assessment will be limited to case studies within selected ecoregions where data and models already have been developed and can be readily incorporated into the assessment framework. The most likely regions include the Mississippi Alluvial Valley, Prairie Pothole Region, southern Florida, and the Chesapeake Bay watershed.

Different ecosystem services have different definitions, ranges, and meanings, so an ecosystem services change indicator (ESCI) has been defined in this report in order to compare them simultaneously:

$$ESCI = \frac{ES - ES_0}{ES_0}, \quad (1)$$

where ES refers to the output value of a selected ecosystem service, and

ES_0 is the corresponding baseline value.

A test that compared the ESCI values for selected ecosystem services was conducted for Tensas Parish, La. (in EPA Level III Ecoregion 73, Mississippi Alluvial Plain), and Clairborne County, Miss. (Ecoregion 74, Mississippi Valley Loess Plains). The changes in selected ecosystem services as they relate to carbon sequestration were considered by using the IPCC SRES A1B storyline (Nakicenovic and others, 2000), the land-cover classes for the two jurisdictions (see figure 3.7), and the “reference land use, land cover, and land management” (R) and the “enhanced land use and land cover with reference land management” (L) scenarios (see section 3.2.2). The results in table 3.15 and figure 3.13 are an example of the model outputs and one method (using ESCI) of comparing changes over time using the IPCC SRES A1B storyline and the R and L scenarios. In practice, ecosystem services will be quantified using multiple models for the assessment and for providing uncertainty estimates. In the table, the modeled timber production as an ecosystem service for the 2041 through 2050 time period for the R and L scenarios is 9.70 and 3.61 grams of carbon per square meter per year (gC/m^2/yr), respectively, although the baseline value for 2001 through 2010 is 4.89 gC/m^2/yr. An ESCI value of greater than zero indicates

Table 3.15. Preliminary ecosystem service estimates for a test in Tensas Parish, La., and Claiborne County, Miss., using the A1B storyline.

[Abbreviations and acronyms are as follows: CH_4, methane; ESCI, ecosystem services change indicator; L, “enhanced land use and land cover with reference land management” scenario; N_2O; nitrous oxide; R, “reference land use, land cover, and land management” scenario]

Assessment data products	Unit of measurement	Baseline value (2001–2010)	R (2041–2050)		L (2041–2050)	
			Output value	ESCI	Output value	ESCI
Net ecosystem productivity	Grams of carbon per square meter per year	651	571	-0.123	575	-0.117
Soil organic carbon	Grams of carbon per square meter	5,433	6,153	0.133	6,155	0.133
Carbon sequestration	Grams of carbon per square meter	6,193	9,872	0.594	10,207	0.648
Timber production	Grams of carbon per square meter per year	4.89	9.70	0.985	3.61	-0.260
Grain production	Grams of carbon per square meter per year	70	57	-0.185	52	-0.252
Carbon storage	Grams of carbon per square meter	12,377	16,810	0.358	17,146	0.385
Carbon sequestration	Grams of carbon per square meter	148	91	-0.384	105	-0.292
N_2O emission	Gigagrams of nitrogen	24.3	21.6	0.112	21.7	0.110
CH_4 emission	Teragrams of carbon	0.163	0.133	0.183	0.143	0.125
Erosion	Tons per hectare per year	-0.062	-0.059	0.049	-0.061	0.008

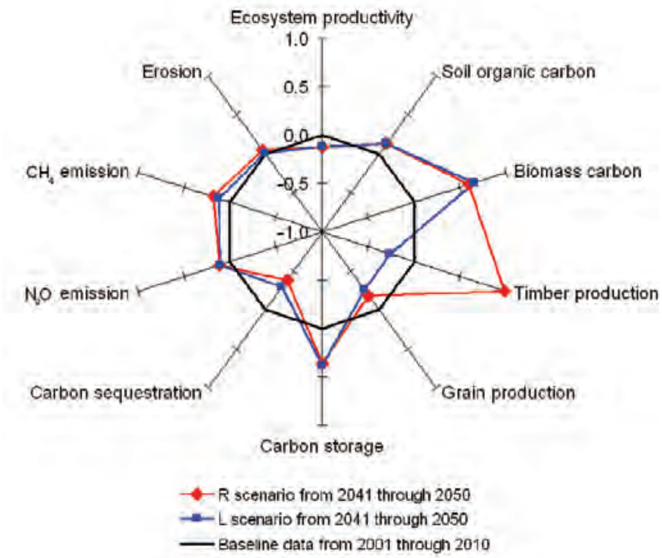

Figure 3.13. Chart showing a comparison of ecosystem service changes using the ecosystem service change indicator (ESCI). Baseline data for 2001 through 2010 are shown along with projected changes from 2041 through 2050 using the "reference land use, land cover, and land management" (R) and the "enhanced land use and land cover" with reference land management" (L) scenarios. Values shown apply to the whole chart.

a positive increase in ecosystem service change compared to baseline (2001–2010); an ESCI value of less than zero indicates a negative change. The ESCI absolute value reflects the magnitude of the ecosystem change.

Analysis of Mitigation Costs and Benefits.—The implementation of mitigation activities to enhance carbon sequestration can result in societal benefits associated with reducing impacts of climate change and can also provide benefits from marketable commodities, such as harvested timber and other ecosystem services. Depending on the activity, the net societal values for carbon sequestration can be positive (societal benefits) or negative (societal costs). Carbon-sequestration activities also have costs, such as the opportunity cost of the land on which to enact a mitigation activity, as well as any associated capital or maintenance costs. This section will explain a simple accounting approach that can be used to estimate the potential benefits and costs of a management activity so that a user will get a "first-cut" approximation of an activity's possible payoff. Both current and potential market and societal benefits and management-activity costs will be included in a discounted cash flow (DCF) analysis (Schaltegger and Burritt, 2000; Wrisberg and de Haes, 2002). A DCF analysis is a widely used valuation tool that will (1) account for both the benefits (the societal benefits of carbon sequestration and any other benefits) and the capital and operating costs of a potential project, and (2) assume the value of money changes over time (discount rate). All future flows of benefits and costs will be estimated and discounted to yield a present value. Assuming that all other relevant market conditions are constant, if the value of the investment is greater than the cost of the investment, the activity will have a positive net present value. An example of the application of this method in Tensas Parish, La., using one potential mitigation activity, is given later in this section.

The assessment methodology will use the DCF analysis to estimate (1) the carbon sequestration and other ecosystem-service benefits as well as any income from a marketed commodity (for example, sawtimber), if applicable; and (2) the economic costs of acquiring the land and implementing a mitigation activity. The benefits and costs will be estimated in terms of the present value of the benefits (PVB) and the present value of the costs (PVC) of a mitigation activity. In addition, the DCF method will be used to associate the benefit and cost information of mitigation activities in one ecoregion with others. Furthermore, the analysis of the benefits and costs of a management activity will not be quantified as constraints for the scenario construction, which are ramifications of land-management activities.

Two types of ecosystem services benefits will be included in the methodology (Jenkins and others, 2010). The first benefit is the market value of a commodity that is sold in traditional markets. The second benefit is the economic value to society in terms of the flow of ecosystem services. Both should be used in societal-benefit and cost analyses of public policies or programs. The present value of the market benefits will be entered into the numerator of equation F1 in appendix F to calculate the present value of benefits (PVB).

Market benefits.—The market value for services provided by a particular ecosystem is based on the commodities that are currently bought and sold in traditional markets. Market values for the economically valuable outputs of certain ecosystems, such as timber (stumpage value), will be estimated using a market price of the output harvested in the year it is sold, which will be assumed to be the final year in which the assessment was conducted; the estimated market value is entered into the DCF. These direct-use services are typically consumptive (for example, commercial fishing, and pharmaceuticals).

Nonmarket benefits.—Some ecosystem services, such as recreational fishing and birdwatching, are not valued in traditional markets (nonmarket values). Although the price of a marketable commodity is determined by willing buyers and sellers in the marketplace, ecosystem services that currently are not traded in a market require alternative ways to estimate their value to society (Merlo and Croitoru, 2005; Richardson and Loomis, 2009).

The measurement and estimation of societal values in the assessment will link ecosystem services to existing valuation methods in order to facilitate the analysis of these externalities by users. For example, economic studies that elicit the willingness to pay either by using economic surveys (Hanemann and others, 1991; Stevens and others, 2000) or by market-based factors (Bernknopf and others, in press) can provide monetary benefit estimates of ecosystem services (Loomis and Helfand, 2001). These types of analyses will be used to estimate the willingness of society to pay for environmental improvements. Brookshire and others (2010) used the stated preference approach to estimate the value of vegetation composition, water availability, bird breeding, and migratory bird abundance in a watershed in the southwestern United States; however, when the resources for conducting an economic analysis in certain places like this one are limited, one approach to economic valuation is to use benefit transfer studies. Benefit transfer studies are a means to adapt a study from one location or region to another. This approach is a way to harness the benefits of existing economic studies while minimizing the need for costly new site-specific analyses (Brookshire and Neill, 1992; Devosouges and others, 1998; Brookshire and Chermak, 2007; Brookshire and others, 2007). The benefit transfer method will be applied in the test described below and will apply the specific results from a preexisting study for valuing several ecosystem services for the Mississippi Alluvial Valley to Tensas Parish, La. (Jenkins and others, 2010). For example, ecosystem societal value estimates will be based on the number of hectares converted from agricultural use to managed forest plantations. The nonmarket benefit estimates will be entered into equation F1 in appendix F to calculate the PVB of these ecosystem services.

Because few markets exist for ecosystem services, the assessment methodology will incorporate the possibility of potential markets for specific ecosystem services such as nitrogen mitigation (Jenkins and others, 2010). Potential markets will be included because of the possibility that, while the assessment is being planned, the markets for ecosystem services will expand and new policies associated with those markets will be implemented. Potential market values can be entered into the numerator of equation F1 in appendix F.

Economic costs.—Land and the cost to implement a mitigation activity will vary over time and space because of the type, size, and design criteria of the mitigation activity; its geographic location; the cost of labor and materials for it; the alternative uses of the targeted land; and the biophysical site characteristics. In the methodology, economic costs will be estimated as a present value (PVC equation F2 in appendix F) and an equivalent annual cost (EAC, which is calculated using equation F3 in appendix F and is derived from the PVC).

The components of cost are: (1) the cost of obtaining the land, and (2) the direct engineering costs[4] involved in the ecological carbon-mitigation activity that has been chosen. The second component includes the following factors: (1) up-front or one-time capital-investment costs for establishment and installation of the mitigation activity, including site preparation, planting, and any initial chemical treatments (and documentation of the environmental impacts of all of the preceding); (2) recurring capital expenses of the activity, such as the expenses related to boundary maintenance; and (3) annual operating, maintenance, and management costs (including performance monitoring, administration, insurance, and other transaction costs). See appendix F for details on these cost categories.

For the test, the economic costs were estimated using methods found in Brown and Kadyszewski (2005), Huang and others (2004), and Atkinson and others (2004). They are shown in table F1 and are computed using equations F2 and F3 in appendix F. These cost estimates were used in the test below for Tensas Parish, La. Other estimates have been developed to assess the engineering costs for afforestation projects (Adams and others, 1996); reviews and summaries of the studies that employ them are found in (Stavins and Richards, 2005).

Test for Estimating the Costs and Benefits of a Mitigation Activity.—In this test, the benefits and costs of a mitigation activity were calculated. The theoretical mitigation activity for the test was the conversion of 10,475 ha of agricultural land to forest in Tensas Parish, La. Specifically, this study compares the cost and benefits of the mitigation activity (foresting the land) with the costs and benefits of the current (or reference) unmitigated agricultural land. The benefits of the marketable sawtimber (timber suitable for sawing) products mentioned below were estimated using equations F4 through F9 in appendix F.

Benefits.—In 2009, if the intent of the mitigation activity included harvesting the timber, the market value for the timber was based on stumpage values of $31.01 per ton for sawtimber (Louisiana Department of Agriculture and Forestry, 2010). By applying equation F1 in appendix F, the present value of the benefits for harvesting the timber for a 40-year period, discounted at 4 percent, for the mitigation activity was calculated to be $303,700 (assuming that all the harvested timber was of sawtimber quality). The timber would be harvested in year 40 of the mitigation activity, which is 2050 for this test.

The test links biophysical outcomes with economic values. The benefits estimate of the ecosystem services is based on the benefit transfer method for the Mississippi Alluvial Valley (EPA Level III ecoregion modified from Omernik (1987)) in Tensas Parish, as estimated by Jenkins and others (2010). The benefits estimate is entered into the numerator of equation F2 in appendix F. The estimates for the mitigation activity are calculated using the same 4 percent discount rate as for the costs and market values calculation described above. The current ($1 per hectare per year) and potential ($396 per hectare per year) market values for carbon sequestration are less than $1 million per year and $4.1 million per year, respectively, although the societal value could range from $1.8 million to $2.3 million per year (a societal value range of $171 to $222 per hectare per year). Two examples of societal benefits would be (1) avoiding loss of wildlife habitat caused by rising temperatures by sequestrating carbon dioxide and other GHG, and (2) wetland preservation to improve water quality. The potential economic value of this service that could be realized is as high as $6.4 million per year; the present value benefits at a 4 percent discount rate would be $61.1 million (calculated using equation F1 in appendix F). Nitrogen mitigation could have potential market ($624 per hectare per year) and social ($1,248 per hectare per year) values of $6.5 million per year and $13.1 million per year, respectively. The potential economic value of this ecosystem service could

[4]Investment and operating costs are incurred for economic production and its environmental impacts and improvements.

be as great as $19.6 million per year; the present value benefits at a 4 percent discount rate would be $387.9 million (calculated using equation F1 in appendix F).

Costs.—The PVC and EAC were estimated using equations F2 and F3 in appendix F with cost data indexed to 2009 dollars (Council of Economic Advisers, 2008, table B–101) (Huang and others, 2004; Brown and Kadyszewski, 2005). The cost estimates are for the analysis of the mitigation activity that converts 10,475 hectares of agricultural land to woody wetlands over a 40-year period in Tensas Parish, under the "enhanced land use and land cover with reference land management" (L) scenario; the assumption is that converting the land from agricultural use to woody wetlands improves the carbon sequestration capacity of that acreage. The potential land and implementation costs would be about $18.5 million (PVC using a cost of $1,766 per hectare discounted at a rate of 4 percent) and $1.4 million per year (EAC at $130 per hectare per year) using the data in table F1 in appendix F.

Net benefits.—The net present value of the mitigation activity (the difference between present values of benefits and costs) ranges between -$18.2 million (assuming marketable timber value only) and $436.9 million (assuming that all potential and societal values for the ecosystem services are realized). Although the mitigation-activity costs may be significant at $18.5 million, the values of the marketable commodities along with the potential values of ecosystem services could be even greater. Thus, depending on the assumptions of the benefits to be included, the return on investment in the mitigation activity could be significant.

3.3.7. Validation Methods

The validation strategy for the national assessment is designed to achieve two overarching objectives: to identify, quantify, and document sources of error that underlie the assessment results, and to guide efforts to increase accuracy through improvements in data collection, model design, sampling design, and other elements of the methodology. The validation effort will focus primarily on the assessment data products; the quality of the input data will be documented by reference to existing reports. (The methodology for validation is found in appendix G.)

Because the assessment deliverables will be produced and reported at the scale of assessment units (EPA Level II ecoregions of Omernik (1987)), validation exercises also will be conducted at that scale. Validation will be conducted for assessment results of the "current" (2001–2010) carbon stocks, carbon sequestration, and GHG fluxes in ecosystem. Because the same methods and model runs will be used to produce results for 2001 through 2050, the validation results for target data products can be considered indicative of future potential assessment.

A set of output data products (estimates) from the assessment of terrestrial and aquatic systems will be the initial

Table 3.16. Partial list of deliverable and intermediate data products targeted for validation, and the corresponding reference data sources and needs.

[For explanations of acronyms, please see "Abbreviations, Acronyms, and Chemical Symbols" in the front of the report. Abbreviations are as follows: GHG, greenhouse gas; km, kilometers; m, meter]

Data products for validation	Reference data sources	Reference data needs
Land-cover and land-use change	LANDFIRE VCT	None.
Wildland fires, and carbon emissions by fires	LANDFIRE MTBS, Consume outputs, NOAA Carbon Tracker	Field plots of changes in aboveground biomass.
Delivery of water to coastal area	USGS streamgage network	None.
Net ecosystem productivity (NEP) by pools and ecosystems	AmeriFlux, NEON, NOAA Carbon Tracker	Additional flux data points.
Net biome productivity (NBP)	AmeriFlux, NEON, NOAA Carbon Tracker	Additional flux data points.
Modeled Leaf Area Index (LAI)	MODIS LAI (1-km resolution)	LAI at less than or equal to 250-m resolution (30-m from Landsat).
Grain yields	USDA NASS and ARS	30-m from Landsat.
Carbon stocks by pools and ecosystems	FIA, LTER, NEON, ARS, GRACEnet	Aboveground biomass data from LIDAR.
Carbon removal by forest harvesting	USFS FIA	None.
Carbon pool size in lake or reservoir sediments	RESIS–II, ad-hoc reports	None.
Methane emission by ecosystems	AmeriFlux, NEON, NOAA Carbon Tracker data, ad-hoc reports	GHG flux data for aquatic and wetland systems.
Nitrous oxide emissions by ecosystems	AmeriFlux, NEON, NOAA Carbon Tracker, ad-hoc reports	GHG flux data for aquatic and wetland systems.
Carbon delivery by rivers to coastal areas	NWIS, SPARROW, NEWS	None.

targets for validation (table 3.16). The target data products will be selected based on their relative importance to the assessment results and the availability of suitable, existing reference data. As a general rule, the validation approach will compare the data products to the best available (most suitable) reference data sets that were produced independently of the national assessment. The validation strategy is adaptable to changes in data availability and information requirements. Depending on the assessment data products and the availability of reference data, probability sampling will be considered as a statistical framework for validation (Stehman and other 2003). Individual assessment data products may be added or removed from the list of validation targets in response to model performance or specific issues that may arise. Additional or improved reference datasets will be incorporated as they become available and when deemed effective in support of validation objectives.

3.3.8. Methods for Assessing and Reporting Uncertainty

Gaps in data, current modeling capabilities, interactions between ecological phenomena, and scientific understanding of the mechanics of these complex interactions can produce large uncertainties in the assessment. The treatment of uncertainties is related to the validation assessment, discussed above. Although validation methods will be used for assessing of current carbon stocks, carbon sequestration, and GHG fluxes, uncertainty in the assessment will be focused mainly on scenarios, data, and methods related to future potential conditions. There are two general sources of uncertainty for the assessment: uncertainty related to the IPCC storyline framework, which is unquantifiable (unpredictable); and uncertainty related to data and methods, which may be quantified and reported. The methods for treating uncertainties in the assessment are designed based on IPCC guidelines on uncertainties (IPCC, 2006). Appendix G provides more detailed discussion.

Uncertainty From the Use of the Storylines and Scenarios.—As noted in the previous discussion of storylines (sections 2.5.1 and 3.2.2), the use of three IPCC SRES storyline (Nakicenovic and others, 2000) will effectively bound the size of the overall uncertainty. In addition, the scenarios for alternative land-use and land-management options (section 3.2.2) will be assessed for their potential effects on enhancing carbon sequestration and reducing GHG fluxes. These scenarios also will produce uncertainty in assessment results. For this methodology, the strategy for treating storyline- or scenario-related uncertainties will involve the following steps:

- Communicating the sources of uncertainty.—Potential sources of uncertainty (see appendix G) include choices of storylines or scenarios and the downscaling process.
- Reducing the unknown uncertainties.—Measures to reduce unknown uncertainties will include (1) downscaling the IPCC SRES storylines based on data and studies rather than on global-scale model outputs; (2) standardizing the downscaling methods, which will be accomplished through consultation sessions with regional experts; and (3) increasing the consistency of the scenario framework by using the same design criteria for each alternative scenario and aligning it with the IPCC SRES storylines.

Uncertainty Related to Data and Assessment Methods.—Although uncertainties related to input data and methods are bound by the storyline and scenario uncertainties discussed above, it is still important to assess and quantify uncertainties related to the data and assessment methods under each of the storylines used. Providing information on quantifiable uncertainties will allow users to evaluate assessment results and the methodology for a given scenario. The sources of uncertainty related to the assessment data and methods include the following: input data; the scarcity of data (such as GHG flux data for different ecosystems) that pertains to the assessment methods and deliverables; the process-model structure and associated parameters that are used to estimate carbon stocks, carbon sequestration, and GHG fluxes; and the interactions between components of the assessment (for example, projecting LULC change and evaluating the effects).

The basic approach for estimating uncertainties related to the data and assessment methods will follow IPCC (2006) recommendations. The input data (including the derived intermediate data products that are produced during the assessment) will be processed to produce joint frequency distributions, which in turn are used in Monte Carlo resampling and simulation runs to estimate uncertainty in the resulting output products. For uncertainties introduced by using different methods or models, multiple model runs and statistical analysis will be used to summarize the relative contributions of the technical components to the final uncertainties. All of the data resulting from the assessment also will be evaluated by experts in consultation sessions. Expert opinions then can be used to assess uncertainties.

The focus of assessing and communicating uncertainties is on quantifying the variability of end results, which will be carbon storage, carbon sequestration, and GHG fluxes; therefore, some uncertainties that may arise during the many parts of the modeling process may have very little effect on the final outcome, which will be summarized and delivered at the scale of assessment units. For example, specific locations of land-cover changes across a homogeneous landscape may be highly uncertain, but they may make very little difference in the overall long-term carbon-sequestration measurement at the scale of the assessment-units.

3.3.9. Requirements of Section 712 of the Energy Independence and Security Act for Measuring and Monitoring

As discussed in chapter 1, section 712 of the EISA (U.S. Congress, 2007) requires that the methodology address the measuring, quantifying, and monitoring of carbon stocks, carbon sequestration, and GHG fluxes across the Nation, including coastal waters and estuaries. These three required tasks are closely related: measurements collected directly or remotely provide the necessary data for quantifying the carbon stocks, carbon sequestration, and GHG fluxes, and the continual, systematic repetition of such measurements constitutes monitoring. The methods that are designed to fulfill the EISA requirement for measuring and monitoring carbon stocks, carbon sequestration, and GHG fluxes include the identification of objectives and data source, and a plan for filling data gaps are summarized below. Detailed information on the method is in appendix H.

Objectives for Measuring and Monitoring.—The principal objectives for measuring and monitoring carbon stocks, carbon sequestration, and GHG fluxes are as follows:

- Periodically quantify carbon stocks, carbon sequestration, GHG fluxes, 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; that is, for 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.

The methodology for measuring and monitoring is designed to support the scope of the national assessment and to be adaptive to changing data resources, improved methodologies, and evolving requirements for data and information, while maintaining consistency, scientific credibility, and transparency.

Methodology for Measuring and Monitoring.—Achieving the above objectives requires the continual coordination and implementation of two major activities:

- Quantification of the relevant data products through the spatial aggregation of measurements and (or) model results
- Provision of the data and information that is required for such quantification and for validation and evaluation of mitigation effectiveness

The methodology for measuring and monitoring for the assessment (appendix H) focuses on the provision of the required data and information. The methodology builds on existing data resources that are created, managed, or supported by various agencies and programs across the Federal Government (such as DOI, USDA, NASA, NOAA, and the National Science Foundation (NSF)) and is designed to be adaptive to changing data resources, improved techniques, and evolving requirements for data and information, while maintaining consistency, scientific credibility, and transparency.

Availablity of Data .—The effectiveness of the methodology for measuring and monitoring will be constrained by the availability of required in situ and other observational data, which often are not uniformly distributed in space or among major ecosystems and pools. Known data gaps or deficiencies are identified in appendix H, along with a strategy for developing new or enhanced measurement capabilities. The strategy for ensuring that adequate data is available for measuring, quantifying, and monitoring focuses on critical data shortages and monitoring needs and includes the following:

- Expanded airborne and ground-based measurements of GHG fluxes in terrestrial and aquatic ecosystems
- Expanded measurements of dissolved and particulate forms of carbon (DOC, DIC, and POC) and nutrients (nitrogen and phosphorus), sedimentation rates, and concentration of organic carbon in sediments of aquatic ecosystems
- Improved remote-sensing capabilities for quantifying and mapping terrestrial biomass and small inland water bodies by developing and applying high-resolution satellite imagery and such promising technologies as small- and large-footprint LIDAR

The successful implementation of this strategy requires partnerships and coordination among government agencies and other organizations.

3.4. Data Products, Deliverables, and Reports

The assessment will generate a large quantity of data products in tabular and map formats; for example, carbon stocks, carbon sequestration, and GHG-flux parameters by ecosystem, pool, scenario, and time period will result from the assessment, as will the associated validation and uncertainty estimates (where appropriate). Assessment results will be reported as the final deliverables. In this section, various data products that will be generated by the methodology are introduced, followed by a discussion of assessment reporting mechanisms.

3.4.1. Data Products

The methodology uses a set of integrated methods to assess carbon stocks, carbon sequestration, and GHG fluxes in relation to major controlling processes (such as LULC change and ecosystem disturbances) and potential mitigation strategies (such as LULC change and land-management change). As a result, both the intermediate data products (such as LULC, wildland fire, and river discharge datasets) and final data products (such as carbon stocks, net biome productivity and ecosystem carbon balance, or CH_4 and N_2O flux derived either as digital maps or tabular data) will be generated by various methods. Table 3.17 lists examples of the data products. For the maps, a common spatial resolution of 250 m is listed as a pixel size used by spatially explicit models; however, the map resolution does not designate the scale of the methodology. The scale of the methodology is set as assessment units, as discussed in section 3.1.2.

Table 3.17. A subset of primary deliverables for the national assessment, by deliverable type.

[For an explanation of acronyms, please see "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report. Abbreviations are as follows: CH_4, methane; kg, kilogram; kgC/ha/yr, kilograms of carbon per hectare per year; kgN/ha/yr, kilograms of nitrogen per hectare per year; MgC, megagrams of carbon; MgC/ha, megagrams of carbon per hectare; MgC/ha/yr; megagrams of carbon per hectare per year; $MgCH_4$,/km^2, megagrams of methane per square kilometer; $MgCO_{2\text{-eq}}$/ha/yr , megagrams of carbon dioxide equivalent per hectare per year; MgDOC/km^2, megagrams of dissolved organic carbon per square kilometer; N_2O, nitrous oxide; TgC, teragrams of carbon; TgC/yr, teragrams of carbon per year]

Product name	Data type	Unit of measurement	Time interval
Net primary productivity (NPP)	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Net ecosystem productivity (NEP)	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Net biome productivity (NBP)	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Net ecosystem carbon balance (NECB)	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Soil carbon stock	Map series and statistics	MgC/ha	Annual for 2001–2050.
Fire-induced carbon emission	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Tree biomass removal	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Grain yields	Map series and statistics	MgC/ha/yr	Annual for 2001–2050.
Carbon stock/flux trends	Statistics	TgC/yr, TgC	Annual for 2001–2050.
Carbon accumulation in lake and reservoir sediments	Statistics	MgC	Annual for 2001–2050.
Carbon accumulation in coastal waters	Statistics	MgC	Annual for 2001–2050
CH_4 efflux	Map series and statistics	kgC/ha/yr	Annual for 2001–2050.
N_2O efflux	Map series and statistics	kgN/ha/yr	Annual for 2001–2050.
Methane flux from lakes, reservoirs	Statistics	$MgCH_4$/km^2	Annual for 2001–2050.
Delivery of organic carbon by rivers to coastal areas	Statistics	MgDOC/km^2	Annual.
Delivery of inorganic carbon by rivers to coastal areas	Statistics	MgDOC/km^2	Annual.
CH_4 and N_2O flux from estuaries and coastal waters	Statistics	$MgCO_{2\text{-eq}}$/ha/yr	Annual.
Land suitability for REDD by NPP, fire disturbance categories, and scenario storylines	Map series and statistics	Thematic classes	Annualized average.
Future soil erosion and surface runoff potential by major ecosystem types and management scenarios	Map series and statistics	Thematic classes	Annualized average.
Greenhouse-gas reduction (N_2O, CH_4) by ecosystem type and LULC and land-management scenario	Map series and statistics	MgC/ha/yr, $MgCO_2$-eq/ha/yr	Annualized average.
Effects of management activities on carbon sequestration	Tabular data	MgC/ha sequestered	Annualized average.
Ancillary effects of mitigation activities on ecosystem services.	Tabular data	Units will vary by service type	Annualized average.
Updated and modified NLCD land-use and land-cover data	Map series	Thematic classes	Annual for 2001–2010.
Projected modified NLCD land-use and land-cover data	Map series	Thematic classes	Annual for 2011–2050.
Wildland fire perimeters and severity	Map series	Thematic classes	Annual for 2001–2010.
Wildland fire perimeters and severity	Map series	Thematic classes	Annual for 2011–2050.
Sediment and nutrient flux to estuaries and coastal waters	Statistics	kg	Monthly and annual.

3.4.2. Assessment Reporting

The methods and format for reporting the results of the assessment will follow the guidelines in IPCC (2006) for reporting carbon stocks, carbon sequestration, and GHG fluxes. For each assessment unit, the types of deliverables to be reported are listed below:

- Estimates of present and future carbon stocks and sequestration by pool, ecosystem, and assessment scenario, and by 10-year intervals
- Estimates of present and future GHG fluxes by pool, ecosystem, and assessment scenario, and by 10-year intervals
- Analyses of biophysical effects (for example, climate, land-cover patterns, or ecosystem disturbances, such as fire) on carbon stocks, carbon sequestration, and GHG fluxes
- Analyses of the effectiveness of potential LULC changes and land-management activities for enhanced carbon sequestration and reduced net GHG emissions
- Analyses of the potential ramifications of mitigation strategies (including analyses of the effects and effectiveness of potential mitigation activities and their effects on other ecosystem services
- Validation and uncertainty estimates and associated analyses for appropriate deliverables and data products

Examples that illustrate the methods by which these assessment results will be reported are presented here for a subset of results and associated estimated uncertainties (table 3.18), for reporting emissions and effects of wildfires and manmade fires (table 3.19), and for validation results (table 3.20). The method, timing, format, and content of reporting the assessment results will be determined early in the assessment process and will be based on actual results.

Table 3.18. Example of a table format for reporting the results of the assessment of carbon stocks, carbon sequestration, and greenhouse gases, including uncertainties, for current or future scenarios depicted in table 3.6.

[The table will be used as part of assessment-unit reports to present results for years encompassed by the assessment (2001–2050). Acronyms are as follows: DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; GHG, greenhouse gases; NBP, net biome productivity; NECB, net ecosystem carbon balance; POC, particulate organic carbon]

Carbon and GHG measurements	Ecosystems				
	Forest	Cropland	Grassland/shrublands	Wetlands	Aquatic habitat
Carbon stocks					
NBP/NECB					
Carbon flux					
N_2O flux					
CH_4 flux					
Lateral carbon flux (DOC, DIC, POC)					
Global warming potential (GWP)					

Table 3.19. Example of a table format for reporting the effects of wildfires and manmade fires on carbon stocks for a given assessment unit, for all ecosystems.

[kgC/m^2/yr, kilograms of carbon per square meter per year]

Wildfire types	Years of the assessment				
	2001–2010, kgC/m^2/yr	2011–2020, kgC/m^2/yr	2021–2030, kgC/m^2/yr	2031–2040, kgC/m^2/yr	2041–2050, kgC/m^2/yr
Prescribed surface fire					
Low-severity wildland fire					
High-severity wildland fire					

Table 3.20. Example of a table format for reporting validation results of comparing the reference data with the 2010 assessment estimates (present conditions) for selected assessment parameters, for a given assessment unit.

Validation target	Measurement units	Estimated value	Mean deviation	Mean absolute deviation	Root mean square error
Forest carbon stock					
Forest carbon emission by fire					
Forest net ecosystem productivity					
Carbon export to coastal waters					

4. Conducting the National Assessment

With the proposed methodology framework and specific methods and models outlined in chapter 3, the focus of this chapter is on implementing the national assessment. This chapter also includes a discussion of science needs, as well as a brief examination of potential applications.

4.1. Operational Issues

In order to implement the EISA-mandated national assessment (U.S. Congress, 2007), several operational and logistical issues, including interagency cooperation, access to required data, assessment prioritization and scheduling, and project management, will need to be addressed. These issues are outlined below.

Interagency cooperation and coordination.—The methodology is the result of a multidisciplinary approach that required cooperation and collaborations with more than one organization. Shared activities included development of the mitigation scenarios, remote sensing, in situ data access, and field validation of assessment results. For the assessment, close coordination with agencies and organizations that conduct relevant resource assessments and research will continue to be necessary. Close cooperation and coordination can be facilitated by organizing an interagency assessment team established for this purpose, with scientists from appropriate organizations coordinating technical exchanges, developing interagency agreements about data sharing, overseeing production of data products, and forming an executive oversight committee to provide high-level support to the assessment.

Engagement of the national and international science community.—The active engagement of the national and international science community throughout the assessment will be necessary to ensure that the results are timely, useful, accessible, and relevant. This engagement will facilitate internal benefits (such as possible advances in scientific areas such as climate change, biogeochemical modeling, or ecosystem disturbances) and external benefits (such as assistance in comparing various models, synthesis workshops, and comparing the assessment results derived using the various models.

Enhancement of data access and management.—The national assessment will require access to numerous datasets from a variety of sources to ensure the quality of the assessment and to minimize the uncertainty of assessment results. Access to some types of data may present varying degrees of difficulty. For example, some datasets are proprietary, some must be acquired through formal acquisition processes (for example, remotely sensed wildfire perimeters and severities), and some will require formal agreements that precisely dictate how to acknowledge credit for providing the data. There also may be difficulty in organizing and managing the data (including the metadata).

Prioritization and scheduling assessment activities.—The methodology uses U.S. Environmental Protection Agency (EPA) Level II ecoregions (Omernik, 1987) as the primary assessment unit so that carbon stocks, carbon sequestration, and GHG fluxes can be assessed one ecoregion at a time, in the context of mitigation scenarios that will be developed specifically for that ecoregion. Federal agencies and other stakeholders will be consulted to prioritize the order in which ecoregions will be assessed. For instance, ecoregions with the greatest potential for increased carbon sequestration, regions that are predicted to experience the most profound impacts from climate-change or land-use and land-cover changes, and regions where established collaborative opportunities already exist may receive the highest priorities. Prioritization also should be based on data quality and availability. For example, Alaska may be assessed at a later time to allow for additional data collection (in situ and remote sensing) and processing.

Active project management.—A well-defined, structured, and scalable project-management process should be established and followed for the assessment. The project-management plan should be developed, organized in structured phases and tasks, and submitted for review by the interagency assessment oversight team. The plan should establish metrics and include all linked dependencies. The project plan will ensure that activities are executed effectively and efficiently, with progress measured against established metrics in order to complete the assessment within the allotted time frame.

4.2. Major Scientific Research and Development Needs

The methodology is based on balanced considerations of the established scientific knowledge, the operational efficiency of methods and models, and the availability of datasets that meet the assessment needs. The gaps in required input data are addressed in chapter 3, which also contains plans for reducing the effects of the data gaps; however, as noted throughout chapter 3 and in the various appendixes, it is crucial to address scientific needs and data gaps to further improve and enhance the ability to accurately assess carbon stocks, carbon sequestration, and GHG fluxes of the Nation's ecosystems. Key areas of research and developemnt are as follows:

Permafrost.—Assessments of permafrost and GHG responses to changes in permafrost would benefit greatly from targeted studies linking permafrost degradation to changes in surface water and GHG fluxes. Although some such studies are underway and their results may be available for the assessment, in situ measurements and model development should be designed to establish probability assessments for hotspots of GHG release; such assessments should be based on field studies in stratified sampling designs by landscape (based on slope and permafrost information), ecosystem (vegetation type, disturbance age), and geohydrologic unit (surficial geology and substrate).

Ecosystem disturbances.—Spatially explicit mapping and modeling of ecosystem disturbances are challenging. Mapping and modeling of wildland fires and anthropogenic disturbances (such as forest cuts) are technically more advanced than modeling other ecosystem disturbances (such as storm damage, and forest defoliation and mortality caused by insect outbreaks). There are national programs that produce spatially explicit datasets of various major ecosystem disturbances, but there is a lack of consensus about their technical standards and readiness for operational applications. Although this methodology documents an approach for spatially mapping, characterizing, and forecasting wildland fires and other disturbances, there is a strong need for continued vetting of the proposed methods by comparing results with other methods and models and by conducting validation exercises using in situ and other fire data.

Wetlands.—Accurate mapping of wetlands and aquatic habitats is a key step in the assessment of different ecosystems; however, despite the availability of national datasets, such as the National Land Cover Database and the National Wetland Inventory, determining the spatial boundaries of wetlands and aquatic habitats will be an early research and development priority in the assessment. Practical methods will be devised to spatially separate upland systems, inland-freshwater systems, inland-wetland systems, coastal-salt-marsh systems, and coastal-aquatic systems. Certain satellites that collect high-resolution data (for example, GeoEye1 and Worldview2) could provide extensive coverage that would aid in mapping these systems. An eight-band sensor on the Worldview 2 satellite provides imagery with a bathymetric wavelength that could be used for measuring and monitoring terrestrial vegetation with the additional benefit of detecting sediment beds of reservoirs, impoundments, and coastal estuaries. These mapping efforts would provide data enabling a better understanding of patch- and landscape-scale controls on carbon stocks, carbon sequestration, and GHG fluxes, including the potential effects of sea-level rise, and would enhance the assessment results for wetlands.

Inland basins, reservoirs, estuaries, and coastal areas.—Few data are available to construct models for determining GHG fluxes and accumulation rates of carbon in sediments in inland basins, reservoirs, estuaries, and coastal areas. Additional data are needed to accurately model fluxes and carbon sequestration as a function of surface-water and groundwater flow of nutrients and sediment into these systems.

Biogeochemical models.—Biogeochemical modeling of carbon stocks, carbon sequestration, and GHG fluxes will be a core capability of the assessment and will incorporate both bookkeeping and process-based modeling methods in order to improve consistency in and enhance the transparency of the overall methodology. The crosscheck and the use of data assimilation techniques, as discussed above, are helpful, but more research and development needs exist, such as the identification and use of other appropriate BGC models based on their unique suitability for different ecosystems, pools, and flux types. Techniques need to be improved for model comparison, result validation or accuracy of the assessment, and implementation of uncertainty assessment.

Integration of the assessments for terrestrial and aquatic ecosystems.—Terrestrial and aquatic ecosystems have different ecological processes that determine GHG fluxes. The assessment of aquatic ecosystems should be dynamically integrated with that of the terrestrial systems so that the relevant terrestrial estimates (for example, rates of surface runoff and erosion) may be used as input data for estimating carbon sequestration in and GHG fluxes from aquatic ecosystems. Research needs to be conducted to link and integrate methods for assessing the interplay between these two types of ecosystems. An application of the research would include the consideration of the tradeoffs between decisionmaking related to the management of water resources versus carbon sequestration and GHG fluxes, as well as inland and coastal sediment management and supply.

Sequestration planning.—One approach to evaluating potential mitigation strategies may be a constrained optimization analysis that combines biophysical feasibility with economic, ecosystem-service, political, and other constraints. To develop a constrained optimization approach, research is needed to develop a mechanism that would provide feedback on the interactions between applying the mitigation scenarios (including the evaluation of costs and the impact on ecosystem services) and modeling the future land-use transitions that might affect carbon sequestration and GHG fluxes. Currently there is no feedback between the models and the mitigation scenarios, which means that the effects and effectiveness of mitigation scenarios are not interactively modeled. The one-way flow from mitigation scenarios to LULC transitions and to changes in carbon sequestration and GHG fluxes limits the range of outcomes for decisions. Sequestration planning will be most useful when a constrained optimization framework is adopted and the sensitivity of planning to the constraints is incorporated to achieve the most sequestration per dollar of cost.

Ecosystem services.—Carbon sequestration and GHG mitigation are just two of the many services provided by ecosystems. Additional research is needed in the following broad areas to improve the ability to evaluate the direct and ancillary effects of carbon-management activities and mitigation strategies on the suite of ecosystem services that are relevant to programs in the U.S. Department of the Interior and other agencies:

- Empirical data and models (statistical, mechanical, driver-stressor-response) that quantify how changes in ecosystem structure and processes affect the quality and quantity of ecosystem services

- Effects of spatial and temporal scales on ecosystem service measurements

- Development of a nationally consistent carbon suitability index for implementing prospective management actions, mitigation strategies, and scenario development

- Integration of socioeconomic, ecological, and natural-science components for measuring and evaluating ecosystem services including valuation, decisionmaking, stakeholders, ecological endpoints, resilience, and sustainability

- Spatially explicit decision-support tools to simultaneously evaluate ecological tradeoffs of multiple services

Uncertainty.—Consistent methods need to be developed and applied for assessing all major sources of uncertainty. The identification of major factors that contribute to uncertainty in estimates of carbon stocks, carbon sequestration, and GHG fluxes will result from a series of sensitivity analyses. These results will help guide the focus of future monitoring efforts. Documentation of levels of uncertainty must be completed, and recommendations for approaches to reducing uncertainty will be developed, where feasible. A comprehensive review of input data uncertainty (for example, variability in forest-inventory data, classification accuracy of land-cover data, and assessment of spatial autocorrelation in input layers) will be conducted to derive distribution functions that can be used in the simulation modeling process. Experiments will be conducted to determine the impact of uncertainty on certain modeling assumptions and decisions (for example, aggregating land-cover categories, choosing the spatial resolution at which modeling is conducted, and comparing results with relevant published literature).

4.3. Intended Applications

Given the legislative requirements of the EISA (discussed in chapter 1), the assessment results are intended to assist in the development of carbon- and GHG-mitigation opportunities and strategies, promote understanding of adaptation needs under different climate-change scenarios, and estimate potential ancillary effects of mitigation actions on other ecosystem services, as well as many other activities. Users of the assessment results are likely to include public policymakers and analysts, Federal, State, and local government officials, nongovernmental organizations, individuals and community stakeholders, and the scientific community.

The methodology is designed to conduct an assessment and improve the understanding of the spatiotemporal distribution of GHG fluxes and carbon-sequestration capacities in ecosystems, as well as effects and effectiveness of a range of future potential climate-change and mitigation scenarios. The assessment will provide information regarding the benefits and possible tradeoffs between policies and land-use activities that enhance carbon sequestration and reduce net GHG emissions. To help inform these choices and permit comparison, the assessment will proceed by ecoregion, providing maps, statistics, and tabular data of existing and potential carbon stocks, carbon sequestration capacity, and GHG reduction. Specific applications include the following:

1. Estimation of the economic payoffs of mitigation activities and the impacts to the landscape and other ecosystem services caused by mitigation activities. The datasets and maps will be compatible for analysis by others who employ econometric models and economic sector models for benefit and cost studies of policies and regulations

2. Measurement of ecosystem-service flows in terms of physical and economic production and impacts that reflect physical, economic, and institutional constraints (for example, services provided by protected lands versus potential carbon-sequestration actions in surrounding lands)

3. Monitoring for resource management by landowners, developers, verifiers, and regulators. To track and forecast changing conditions, the methodology uses remote sensing to assess land-area changes at the resolution of 250 m that can be aggregated first to EPA Level II ecoregions and then to a national scale

4. Identification of potential disturbance regimes (for example, wildfires) and the effects of land-management actions (such as fuel treatments) to help inform decisions about the risks and opportunities of land-management activities related to natural and human hazards

These applications are consistent with other evaluation measurements and decision frameworks used by resource managers to achieve the maximum increase in carbon-sequestration capacity and GHG reduction. The results of the assessment should be a complement to economic policy models already in use by the EPA and the USDA to analyze the impact of policies related to climate change. This assessment does not, however, include macroeconomic policy analysis with the objective to allocate resources among economic sectors, nor will it contain a microeconomic model of individual investment opportunities and behavior. Rather, the assessment will be an estimate of carbon sequestration capacity and mitigation costs in ecosystems, as determined by land cover, land use, land management, and climate projections, but not determined by the influence of the market economy and individual behavioral decisions.

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Glossary

afforestation The process of establishing trees on land that is not a forest, or has not been a forest for a long time, by planting trees or their seeds.

allochthonous From the outside, such as energy or nutrients that come from outside an ecosystem.

anaerobic An environment where atmospheric oxygen is absent, or an organism that doesn't require oxygen to function.

ancillary effect A positive or negative effect that is subordinate to the primary goal or the intended impact of a strategy, policy, or management action, including unintended consequences. For example, planting more trees to increase carbon sequestration may have the ancillary effect of increasing bird habitat.

assessment A quantitative evaluation of present and future. For this report, it is specifically an evaluation of carbon stocks, carbon sequestration, and greenhouse-gas fluxes in ecosystems.

assessment units Synonymous with the U.S. Environmental Protection Agency (EPA) Level II ecoregions (Omernik, 1987) and watersheds that are aligned, to the extent possible, with boundaries of the ecoregions. Coastal areas also are considered to be assessment units.

autochthonous From within, such as energy or nutrients that come from within an ecosystem.

baseline The reference for a measurable quantity against which an alternative outcome can be measured. A baseline can be static and can serve as an initial or starting condition. A baseline can also be dynamic and serve as a reference line for a defined set of conditions through time.

biome A general ecosystem classification, including forests, grasslands, and wetlands.

carbon burial In this report, refers to deposition of organic carbon and subsequent burial by inorganic sediments in lake, impoundment, stream, estuarine, and marine systems. Carbon also may be sequestered (sometime referred to as "buried") by injection of CO_2 into suitable underground geologic formations.

carbon sequestration The removal of carbon dioxide from the atmosphere and its storage in ecological sinks (components of terrestrial or aquatic ecosystems).

conservation tillage Reduced tillage that is defined, in part, by limited cultivation and retention of plant residues on the soil surface.

contingent valuation A survey-based technique to collect information to determine the value of a nonmarket resource, such as protecting the environment or an ecosystem service.

crop rotation Sequentially growing different crops in the same field or area to (1) avoid the buildup of pests such as insects and pathogens, and (2) replenish nutrients and soil structure.

denitrification The process of converting nitrate or nitrite to nitrogen containing gases like nitrous oxide by microbial processes.

deforestation The process of removing or clearing trees from forested land.

ecophysiology An area of plant ecology that investigates the relation between an organism's function and its surrounding environment.

ecosystem A natural system that is formed by the interaction of a group of organisms with their environment.

ecosystem disturbance An episodic event that may affect the composition, structure, and (or) function of an ecosystem.

ecosystem service The benefits that people and societies derive from the natural processes that sustain ecosystems.

emission A discharge or release, such as discharging greenhouse gases into the atmosphere through natural processes and human activity.

evapotranspiration A compound term used to describe the process of evaporation and plant transpiration. Evaporation accounts for the movement of water to the atmosphere from surfaces such as soils, plant canopies, and water bodies. Transpiration refers to the evaporation of water from plant leaves.

externality The economic impact on a party that is not directly involved in a transaction. In such a case, prices do not reflect the full costs or benefits in production or consumption of a product or service.

flux A flow of an entity, such as the flow of carbon from one pool to another.

flux tower A tower with instruments (for example, an anemometer that measures windspeed) that gives estimates of heat, water, and gas flux in the atmosphere.

gross primary productivity The sum of carbon fixation by plants. Photosynthesis is the process by which plants fix atmospheric carbon and assimilate it within the plant biomass.

inventory A sampling-based data collection and quantitative evaluation of recent natural resource conditions.

land cover The vegetative or other surface cover of a landscape, such as forests, grasslands, wetlands, or barren.

land use The use of land by humans, typically referring to the economic use of the land, such as for residential, agricultural, or manufacturing.

lateral flux The transport of particulate inorganic and organic carbon and dissolved organic and inorganic carbon by rivers. A portion of this carbon is deposited in inland basins, waterways, coastal areas, and oceans.

methanogensisis A form of anaerobic respiration by microbes that produces methane.

mitigation Human actions to reduce the sources of or enhance the sinks of greenhouse gases.

monitoring The systematic collection and analysis of repeated measurements or observations through time.

net ecosystem exchange A value that reflects the net exchange of carbon between the land or ocean and the atmosphere, and equals the net ecosystem production minus the transport of carbon to groundwater or to deep ocean water.

net ecosystem carbon balance A value that reflects the overall carbon balance from all sources and sinks in an ecosystem, whether the sources are physical, biological, and human (including runoff and lateral transport by rivers).

net ecosystem production The net annual carbon accumulation by an ecosystem, which is calculated by subtracting ecosystem respiration from the gross primary productivity, and refers to the amount of organic carbon fixed in an ecosystem that is not respired there and is therefore available for accumulation, export, or oxidation.

net primary productivity The amount of new plant material produced annually, which is calculated by subtracting plant respiration from the gross primary productivity.

nitrification The process of converting ammonium to nitrate by microbial processes.

opportunity cost What must be given up in terms of the next best alternative in making a decision. Any decision that involves a choice between two or more options has an opportunity cost. It does not have to be measured in dollars.

pool A natural region or artificial holding area containing an accumulation of carbon or having the potential to accumulate carbon.

primary productivity The process of converting carbon dioxide, water, and solar energy into plant biomass.

reforestation The process of establishing a new forest by planting or seeding trees in an area where trees have previously grown.

reporting units Equivalent to assessment units. Synonymous with the U.S. Environmental Protection Agency (EPA) Level II ecoregions (Omernik, 1987) and watersheds that are aligned, to the extent possible, with boundaries of the ecoregions.

risk A chance for injury or loss. In this report, it refers to the range of potential values of certain carbon-sequestration capacities or greenhouse-gas fluxes given certain environmental, economic, and policy conditions. It also refers to the potential harm or benefit to the environment because of a particular mitigation action implemented to maximize carbon sequestration.

scenario A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (for example, land-use and land-cover changes) and relations.

sink A natural region or artificial holding area in which the amount of carbon is accumulating.

soil organic carbon The amount of organic carbon held in the soil.

source A natural region or artificial holding area in which the amount of carbon is decreasing.

stock The amount or quantity of carbon contained in a natural region or artificial holding area.

storyline Narratives developed by the Intergovernmental Panel on Climate Change (IPCC) to describe consistent relations between the driving forces that cause greenhouse-gas emissions and provide context for scenario quantification. Each storyline represents a different set of demographic, technological, and economic developments.

uncertainty The inability to precisely know properties (such as the magnitude or position) of a quantifiable parameter for estimating and projecting carbon-sequestration capacities and greenhouse-gas fluxes.

validation Quantitative evaluation of the quality of the input and (or) output data products of the assessment.