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

Scientific Investigations Report 2010–5233

Front of cover.   Photograph of a ranch in the Green River valley in the Rocky Mountains of western Wyoming. Note the willow along the river, sagebrush around the outbuilding and at lower elevations, the open meadow, and aspen trees transitioning to conifers at higher elevations. Forests, grasslands/shrublands, and aquatic ecosystems are represented in this view. Photograph by Donald O. Ohlen, U.S. Geological Survey.

Inside of cover.   Panoramic photograph of a forested area in Yellowstone National Park, northwestern Wyoming, showing the regeneration of lodgepole pines after the 1988 wildland fires. Photograph by Donald O. Ohlen, U.S. Geological Survey

Back of cover.   Photograph of the Park Range Mountains in the Routt National Forest, south of Steamboat Springs, north-central Colorado, showing various shades of autumn foliage in a mixed forest consisting of lodgepole pine, Douglas fir, and aspen. Photograph by Zhiliang Zhu, U.S. Geological Survey.

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

Acknowledgments

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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:

$$°F = (1.8 \times °C) + 32$$

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
API	appication programming interface
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
ESRI	Environmental Systems Research Institute
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 gas

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$_2$O	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 (NRCS)
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, Inc.
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
WCS	Web Coverage Service
WFS	Web Feature Service
WHIP	Wildlife Habitats Incentives Program
WMS	Web Map Service
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—

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(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, non-governmental 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

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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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Executive Summary

This methodology[14] 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), the 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 forests,

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[5]U.S. Geological Survey, Flagstaff, Ariz.

[6]U.S. Geological Survey, Leetown, W. Va.

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[10]Virginia Polytechnic Institute and State University, Blacksburg, Va.

[11]U.S. Forest Service, Missoula, Mont.

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

[13]U.S. Geological Survey, Boulder, Colo.

[14]Supersedes U.S. Geological Survey Open-File Report 2010–1144.

grasslands/shrublands, croplands, wetlands, and aquatic eco-systems (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 ecosystems 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, grasslands/shrublands, and aquatic ecosystems) 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, grasslands/shrublands, and aquatic ecosystems 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.

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 caused largely 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 impacts on the climate. 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 commonly considered in both global and national carbon assessments and in inventories include forests, croplands, grasslands/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 the 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
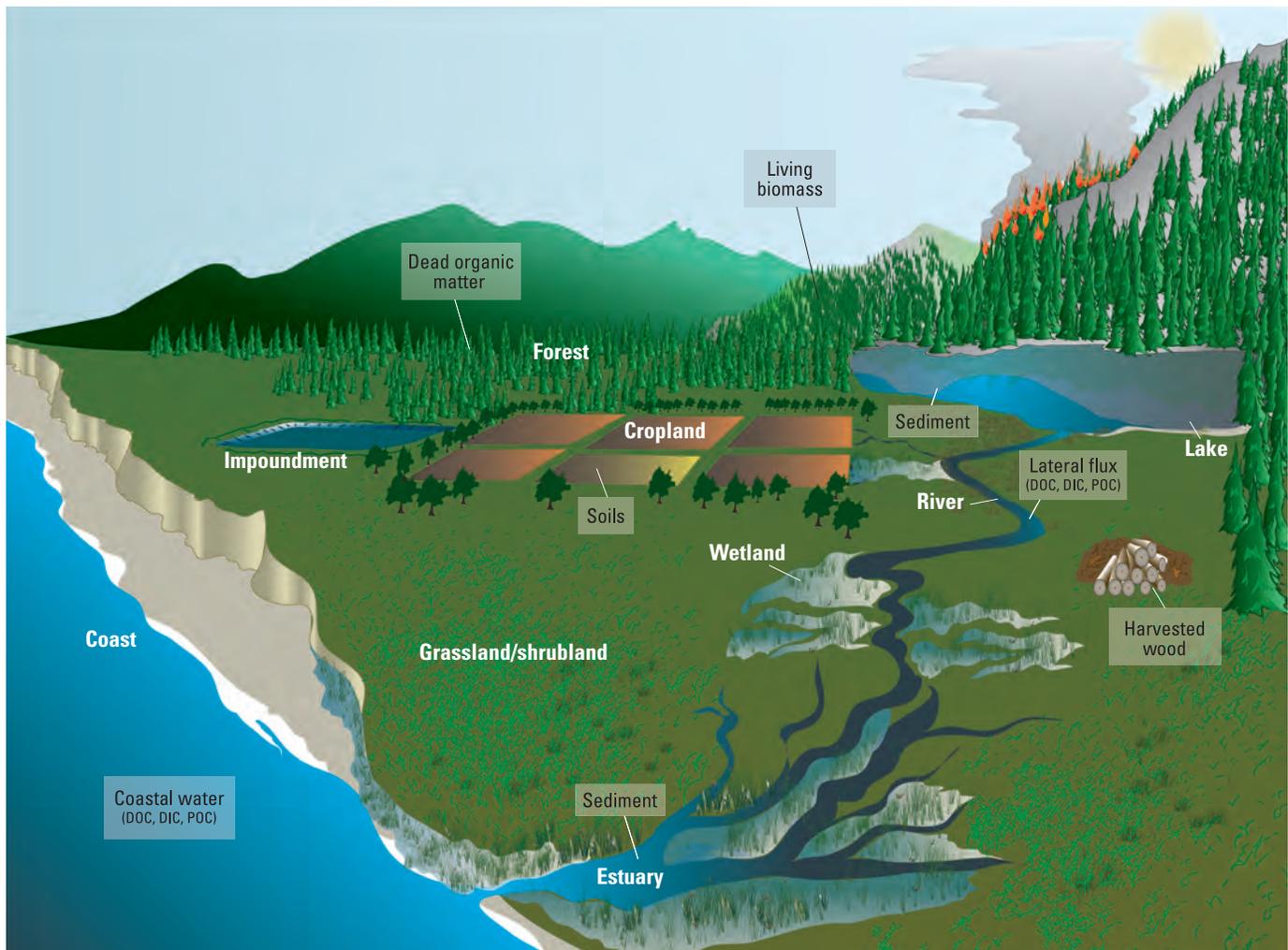
Figure 2.1.   Diagram showing the terrestrial ecosystems covered in the assessment and the major carbon pools (in boxes). Abbreviations as follows: DIC, dissolved inorganic carbon; DOC; dissolved organic carbon; POC, particulate organic carbon.

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
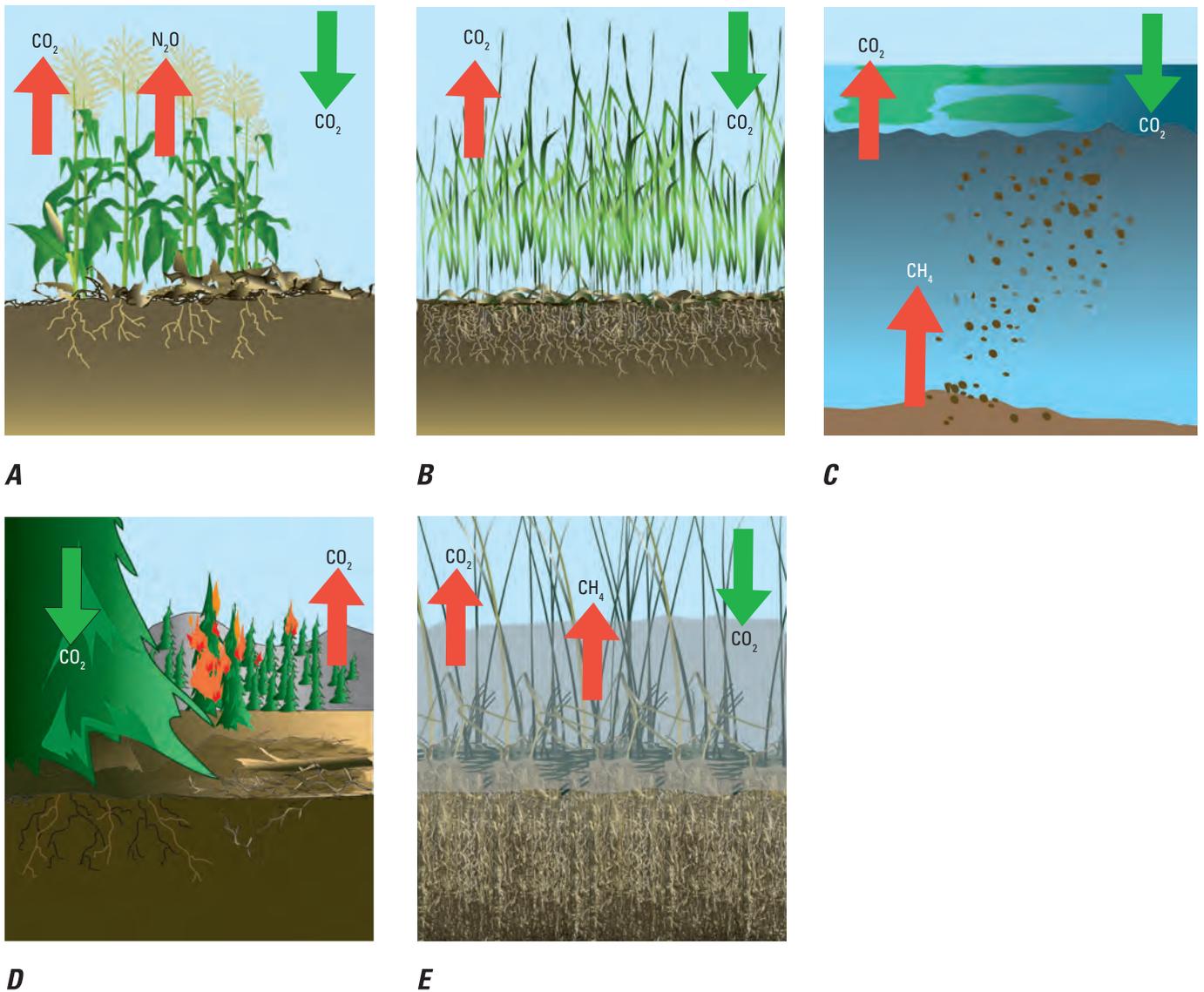
Figure 2.2.   Diagrams showing examples of measured greenhouse-gas (GHG) fluxes in representative ecosystems. The three GHGs covered in the assessment are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Across all ecosystems, CO_2 is emitted via biomass decomposition and respiration and CO_2 is taken up by photosynthesis. *A*, Croplands. Because of fertilizer amendments to cropland soils, emission of N_2O via denitrification often occurs from this ecosystem. *B*, Grasslands/shrublands. Belowground biomass and litter incorporation into the soil contribute to large carbon stocks in grassland soils. *C*, Aquatic ecosystems. Surface water-atmosphere exchange of CO_2 occurs in water bodies. Methane results from anaerobic respiration of buried sediments. *D*, Forest. Large amounts of CO_2 are stored in forest biomass, but carbon can be emitted through combustion of organic matter in forest fires. *E*, Wetlands. Wetlands store large amounts of carbon in organic matter, but anaerobic conditions drive CH_4 emissions into the atmosphere.

States and Alaska, croplands cover about 134 million hectares, and the cropland carbon stock for these regions is about 16 Pg (Bliss, 2003).

Grasslands/shrublands 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. Grasslands/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 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]	–	–
Grasslands/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
Rivers[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]Refers only to lateral flux via rivers.

[g]Source: Pacala and others (2001).

2.3. Effects of Major Controlling Processes

2.3.1. Effects of Changes in Land Use, Land Cover, and Land Management

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).

Grasslands/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, grasslands/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 grasslands/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. 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 sequestered 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, impounds, 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 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

Sustaining and Restoring Ecosystems: Structure to Function to Services
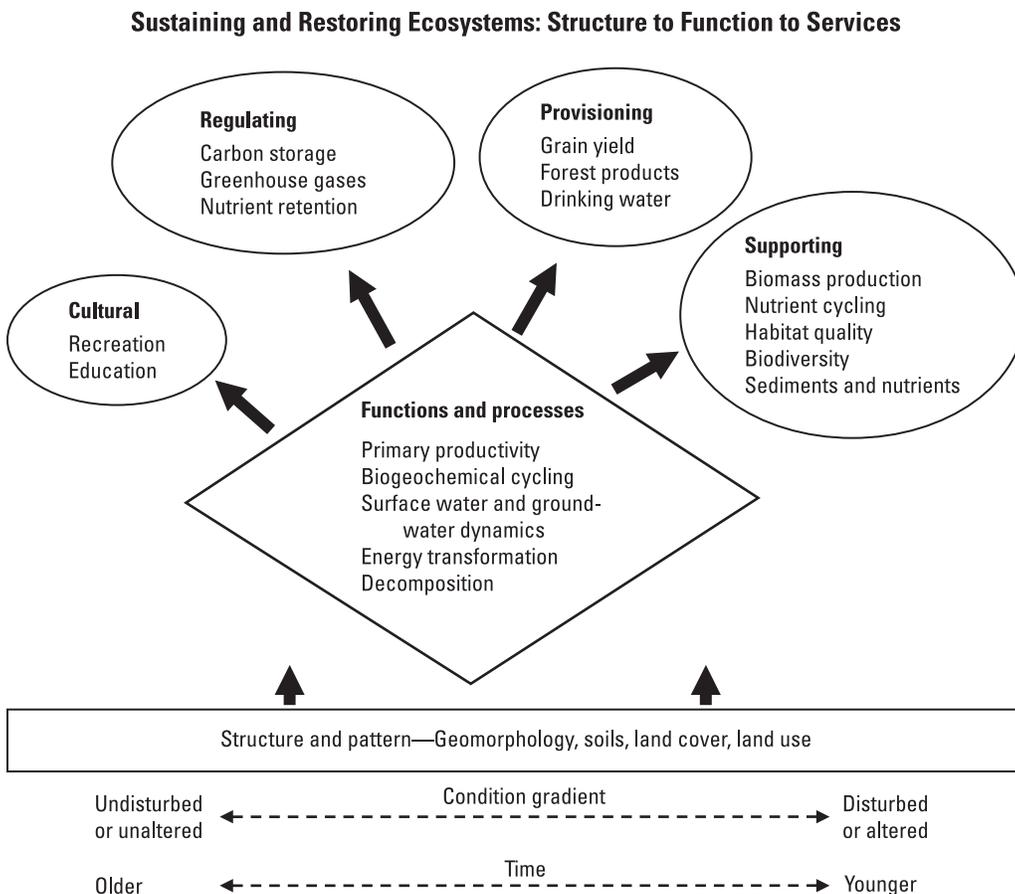
Figure 2.3. Conceptual diagram of the relations among ecosystem structure, function, and services.

IPCC (Nakicenovic and others, 2000). The SRES framework provides assumptions about future potential socioeconomic, demographic, and technological changes that serve as story-lines 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 sce-narios: 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 intro-duction of new technologies until the middle of the 21st cen-tury, 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 adap-tation 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 mate-rial goods and strives to introduce more environmentally sus-tainable 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 technolo-gies 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 treatments of those changes. In describing the approaches, the IPCC recom-mended six standard AFOLU categories for consistent and comparable reporting: forest land, cropland, grassland, wet-lands, 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 car-bon 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 Car-bon Accounting System (NCAS; Richards and Brack, 2004). Carbon stocks and GHG fluxes are inventoried and forecasted in spatially and temporally explicit fashions for major ecosys-tems (such as forests, grasslands, and croplands) by consider-ing 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 incremen-tally reported. In 2007, the most recent year for which report-ing 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 Aus-tralia for both GHG accounting and monitoring purposes.

A recent European Union-wide assessment was con-ducted for terrestrial ecosystems to assess carbon and GHG (N_2O, CH_4) fluxes into and out of forest and cropland ecosys-tems. A compilation approach for the assessment used dif-ferent methods (inventory accounting, process-based ecosys-tem models, and direct remote sensing) and source datasets (national forest or soil inventory, flux tower, and remote-sens-ing 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 follow-ing 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 productiv-ity (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.

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

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.

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 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.

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

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 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).

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 the 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 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. Scope of Assessment

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). Ecoregions are large geographic regions that exhibit relatively unique and similar biotic and abiotic characteristics of ecosystems at the chosen scale (Omernik, 2004; Bailey, 2009). There are 23 modified EPA level II 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. Within each level II ecoregion, scenario development, modeling, and analysis of results will be conducted to characterize within-region variations in resource conditions. The assessment of within-region variations can be made possible by using EPA level III ecoregions nested within level II ecoregions. 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 methodology for the assessment, the ecosystem terms used in this report are defined as broad, regionally unique types of forests, grasslands/shrublands, croplands, wetlands, and aquatic ecosystems (table 3.1). The use of these broad, regionally unique 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 an aquatic pool, which accounts for carbon that is exported by rivers and streams and is used to evaluate the effects of

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).
Grasslands/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 ecosystems	Lakes, impoundments, estuaries, coastal waters, ponds, rivers, and other inland water bodies (combined use of NLCD, NHD, NID, DLG, and NWI).
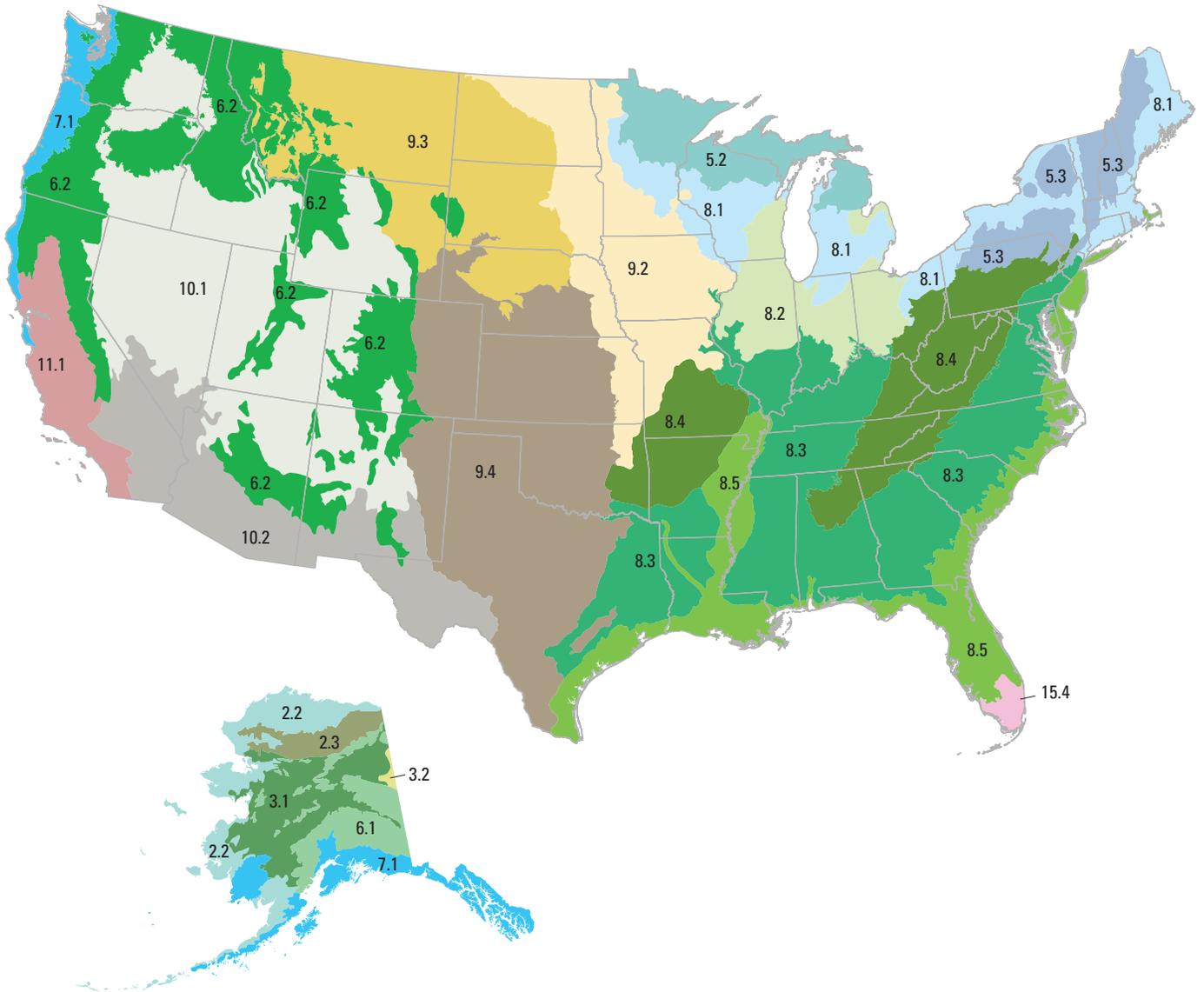
EXPLANATION

Conterminous United States ecoregions

- 5.2 Mixed Wood Shield
- 5.3 Atlantic Shield
- 6.2 Western Cordillera/Upper Gila Mountains
- 7.1 Marine West Coast Forests
- 8.1 Mixed Wood Plains
- 8.2 Central United States Plains
- 8.3 Southeastern United States Plains
- 8.4 Ozark Ouachita-Appalachian Forests

- 8.5 Mississippi Alluvial and Southeast Coastal Plain
- 9.2 Temperate Prairies
- 9.3 West-Central Semiarid Prairies
- 9.4 South-Central Prairies and Southern Texas Plain
- 10.1 Cold Deserts
- 10.2 Warm Deserts
- 11.1 Mediterranean California
- 15.4 Everglades

Alaska ecoregions

- 2.2 Alaska Tundra
- 2.3 Brooks Range Tundra
- 3.1 Alaska Boreal Interior
- 3.2 Tiaga Cordillera
- 6.1 Boreal Cordillera
- 7.1 Marine West Forests

Figure 3.1.   Map showing level II ecoregions of the U.S. Environmental Protection Agency. 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. Ecoregion boundaries within the United States are based on Omernik (1987); within Alaska, they are based on Commission for Environmental Cooperation Working Group (1997). Hawaii is not shown, although it will be addressed in the assessment.

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 dead wood	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. Also includes live fine roots less than 2 mm in diameter as these cannot be distinguished empirically from the litter and dead wood.
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.
Aquatic environment	
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.

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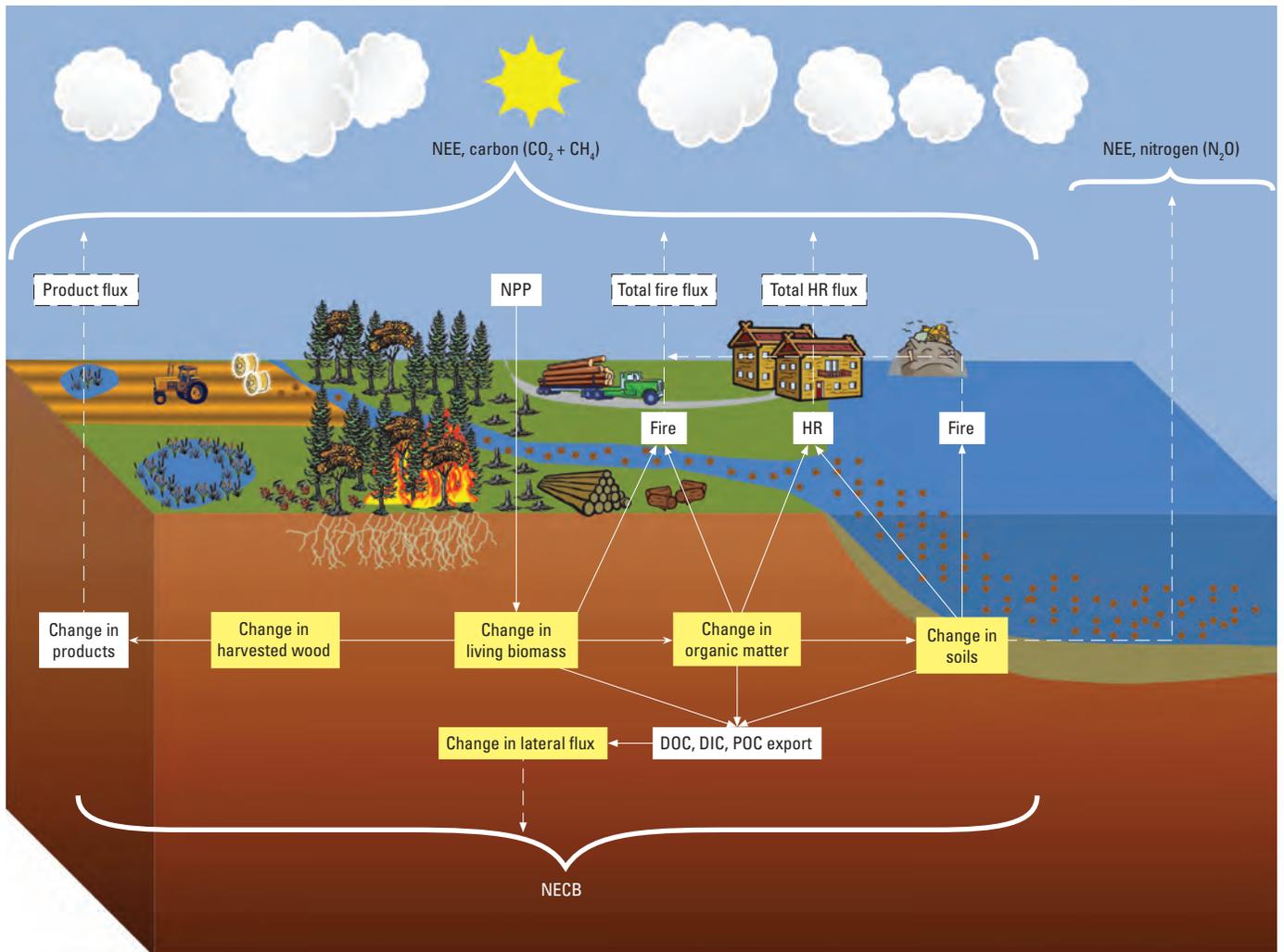
Figure 3.2.   Diagram showing fluxes of carbon (as carbon dioxide and methane) and nitrogen (as nitrous oxide) and exchanges among the primary carbon pools (yellow boxes). Abbreviations are as follows: CH_4, methane; CO_2, carbon dioxide; DIC, dissolved inorganic carbon; DOC, dissolved organic carbon;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

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 assessment will be limited to the requirements set forth by section 712 of the EISA, as detailed in chapter 1. The scope also will be limited by the availability of resources.

- 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

Relation to Existing Inventory and Accounting Methods.—This methodology must be designed to maintain consistency with other existing inventory and assessment guidelines and 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 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

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.

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 greater 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 greater 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 greater 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 greater 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.

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 Ecosystems.—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 ecosystems in this assessment include coastal waters, estuaries, streams, rivers, lakes, impoundments, and other inland water bodies. Aquatic ecosystems 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 ecosystems 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 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."
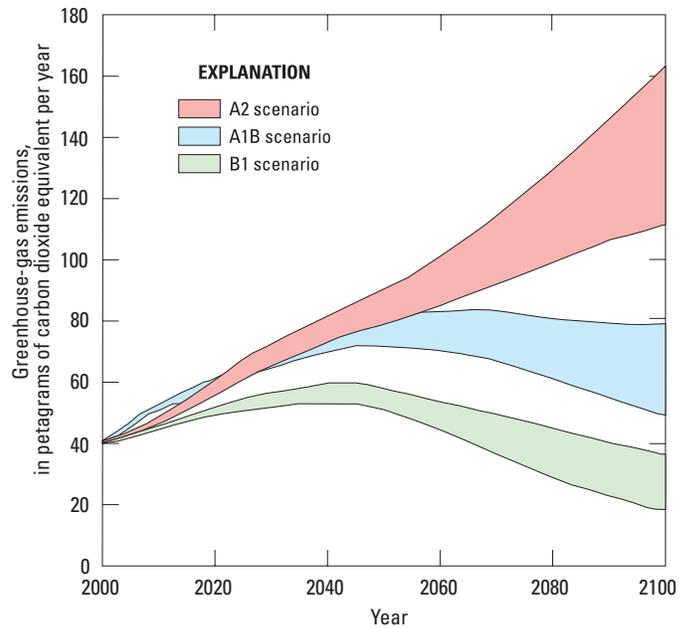
Figure 3.3.   Graph showing hypothetical emission ranges for each of three scenarios defined by Nakicenovic and others (2000). The scenario framework will allow assessment of potential carbon sequestration capacities and associated uncertainties within each scenario and mitigation potential of GHG fluxes across the scenarios. Emissions are in petagrams of carbon dioxide equivalent per year (PgCO$_2$ eq/yr).

Scenarios 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:

- 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

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.
Grasslands/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 fires	Reduce conversion of grassland to energy-producing crops.
Wetlands	Carbon sequestration	Unknown	Restore wetlands.
	Mitigation of net GHG emissions	Unknown	Preserve wetlands.
Aquatic ecosystems	Mitigation of net GHG emissions	Reduce nutrient export from urban and agricultural lands Alter withdrawal from deep reservoirs	

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 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

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 greenhouse-gas (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 GHG fluxes. Finally, a potential natural vegetation (PNV) is introduced as a separate scenario. LULC, land use and land cover.

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.

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. 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, hardscapes, or parcels of land that rarely revert to another land use once they are 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, shrubs, 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 conservation under overall influences of the biophysical environment as maintained by natural disturbances (Sundquist and others, 2009). No new PNV maps will be developed by this assessment. Instead, the assessment will examine existing sources of PNV datasets such as the biophysical settings map produced by LANDFIRE (Rollins, 2009) and the global potential vegetation maps reported by Daly and others (2000) and Gonzalez and others (2010), and make necessary modifications or updates, if necessary.

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, 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

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 enhanced 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

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.

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.

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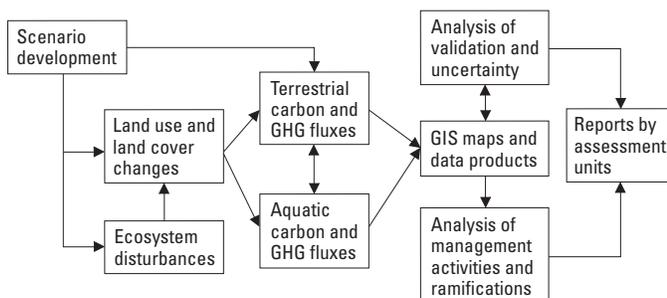
Figure 3.5. Diagram showing relations among major methods that are designed to run scenarios and produce assessment deliverables. These methods (statistical models, analyses, process models, or simple algorithms) are introduced in sections below. Abbreviations are as follows: GIS, geographic information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

- 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 vegetation 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)

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 measurements of agricultural 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.
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- and tornado-track archives	Line segments	Disturbance.

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
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	Variably 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.

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 ecosystems 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 ecosystems 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 ecosystems 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. Downscaled datasets exist (for example, Maurer and others (2007) and Conservation International (2009)). These datasets will be examined to ensure that they meet the data criteria of fine temporal resolution (monthly) for simulations, appropriate parameters (maximum and minimum temperature and precipitation), and fine spatial resolution (4 km) for the three IPCC SRES emission scenarios of interest (A1B, A2, and B1). If it is necessary to downscale and process the GCM data for use by the assessment, "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 20th century (IPCC, 2007), which uses GCM baseline conditions, with output for the three IPCC SRES emission scenarios (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 are listed as examples; these GCMs meet the criteria listed above for use by the assessment.

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

Table 3.8.   Examples of general circulation models that are suitable for use by the national assessment.

[Output from these GCM models may 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.

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. 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 the 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 typically will be 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

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. Ecoregion 73, Mississippi Alluvial Plain; Ecoregion 74, Mississippi Valley Loess Plains.

EXPLANATION

Land cover (parts *A–D*)
- Open water
- Urban/developed
- Clearcut
- Barren
- Deciduous forest
- Mixed forest
- Evergreen forest
- Row crop
- Hay/pasture
- Woody wetland
- Herbaceous wetland

Land-cover change (parts *E–F*)
- No change
- Urban/developed
- Clearcut
- Afforestation
- Woody wetland restoration
- Other change

A

B 2010 "Current" land cover

C 2050 Projected land cover R scenario

D 2050 Projected land cover L scenario

E 2010–2050 Land cover change R scenario

F 2010–2050 Land cover change L scenario

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 in red on the map), were selected to run the scenarios that are shown in the enlargements (parts *B–F*). Grey areas are other level III ecoregions. *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*.

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 stocks, carbon sequestration, and GHG fluxes.

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

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, and damaging winds	Storm tracks, severity, and areas of mortality	RSLC.
Insects 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.

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, or 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 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 locations was used (with ignition points limited to natural vegetation types, such as is found in forests, grasslands/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 the Western United States). Predicting fire occurrence and spread is an 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) 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
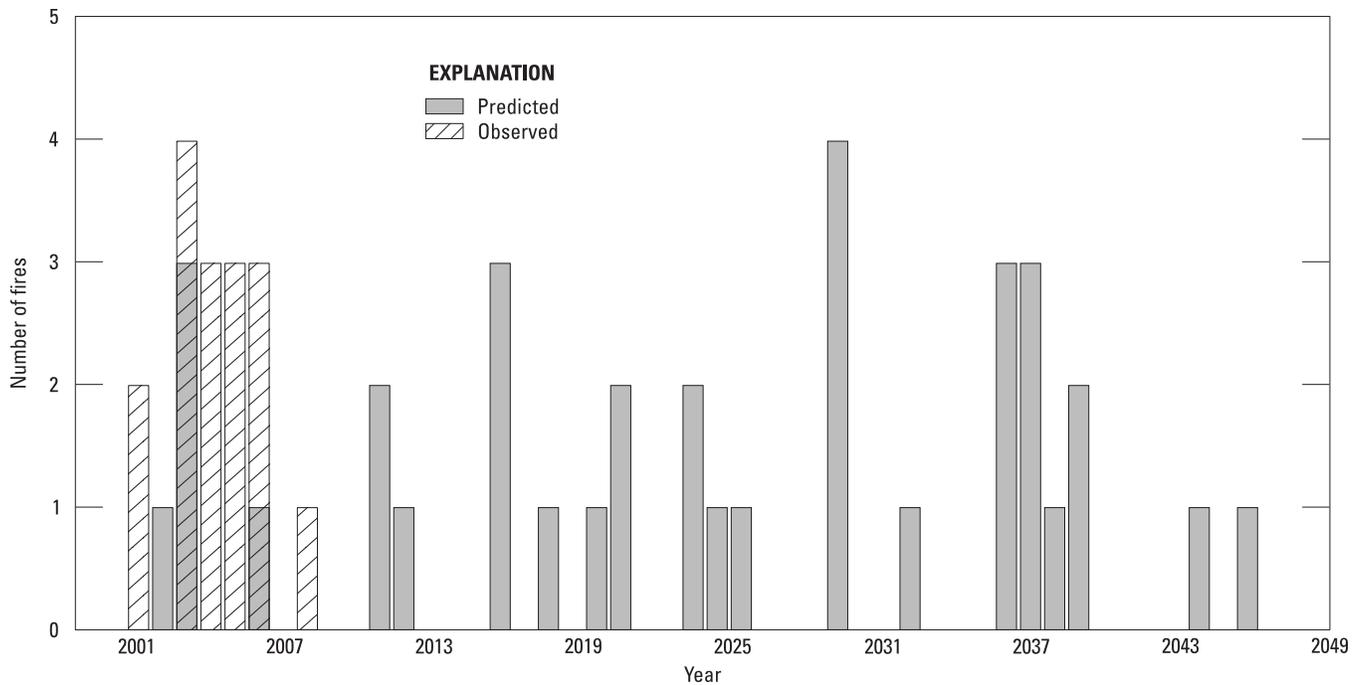
A
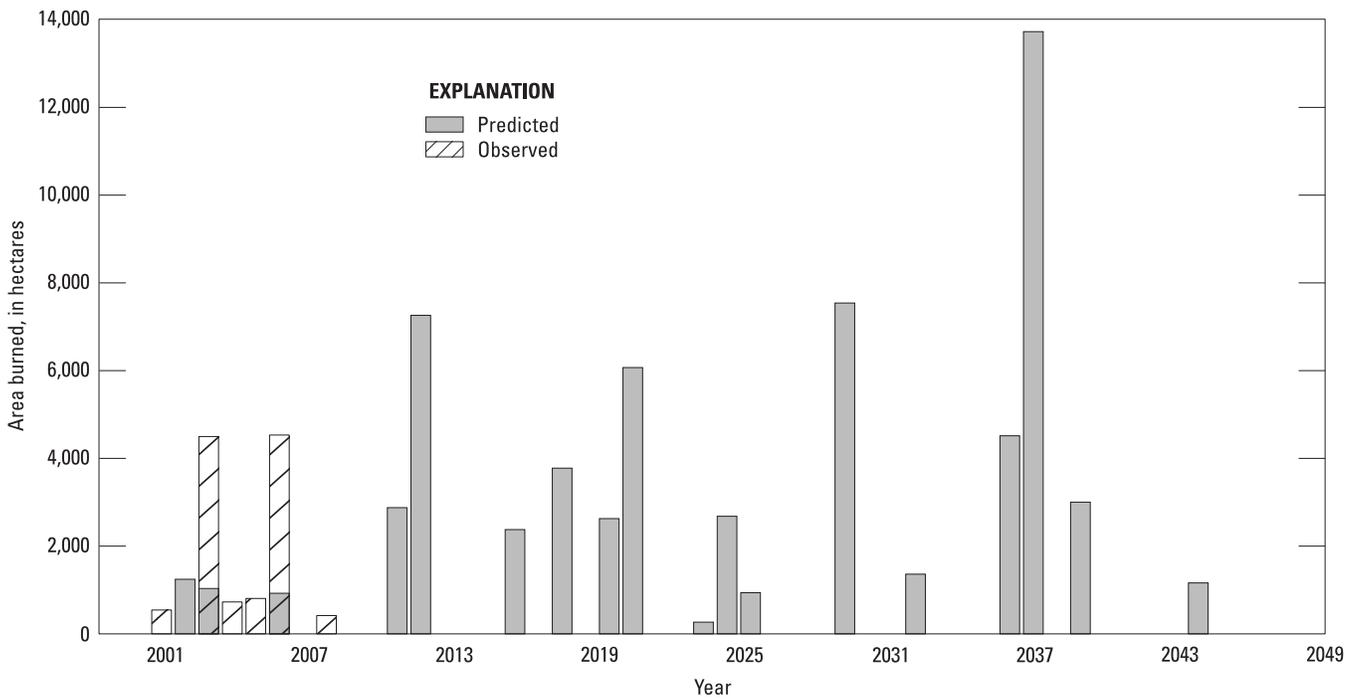
B

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. *A* and *B*, Mississippi Aluvial Plain; *C* and *D*, Mississippi Valley Loess Plains.
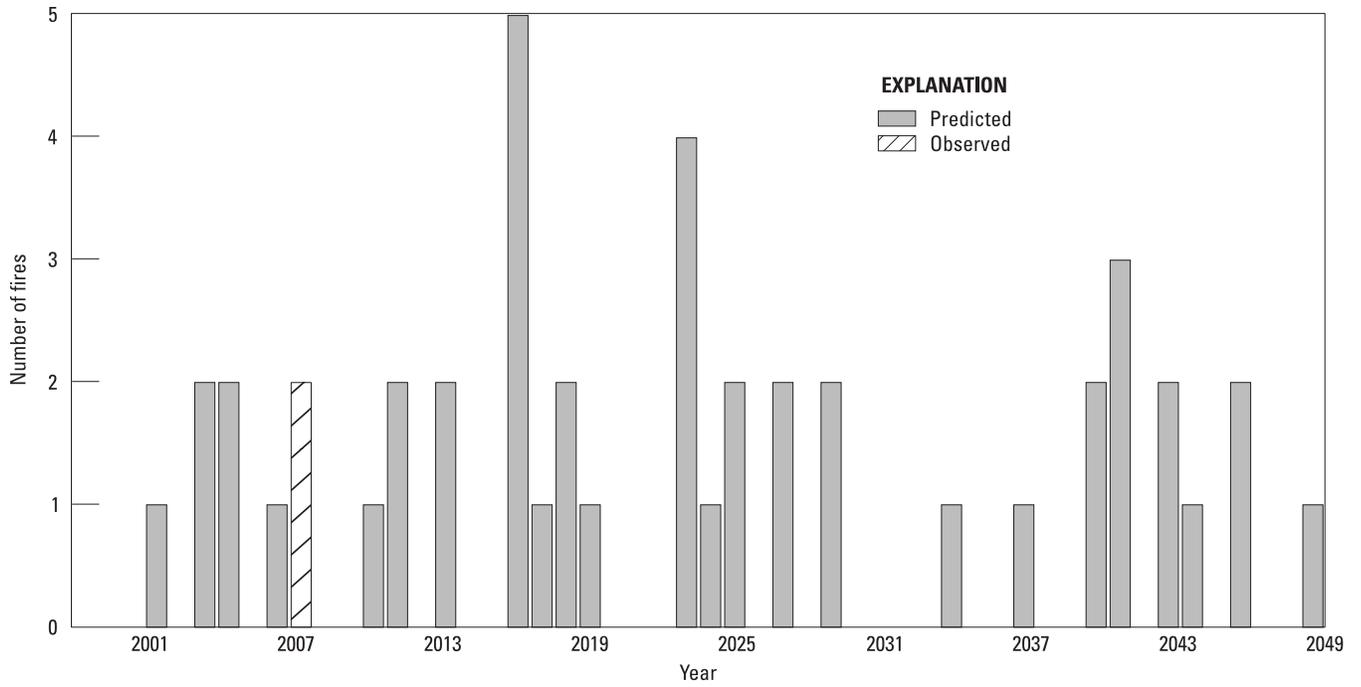
C
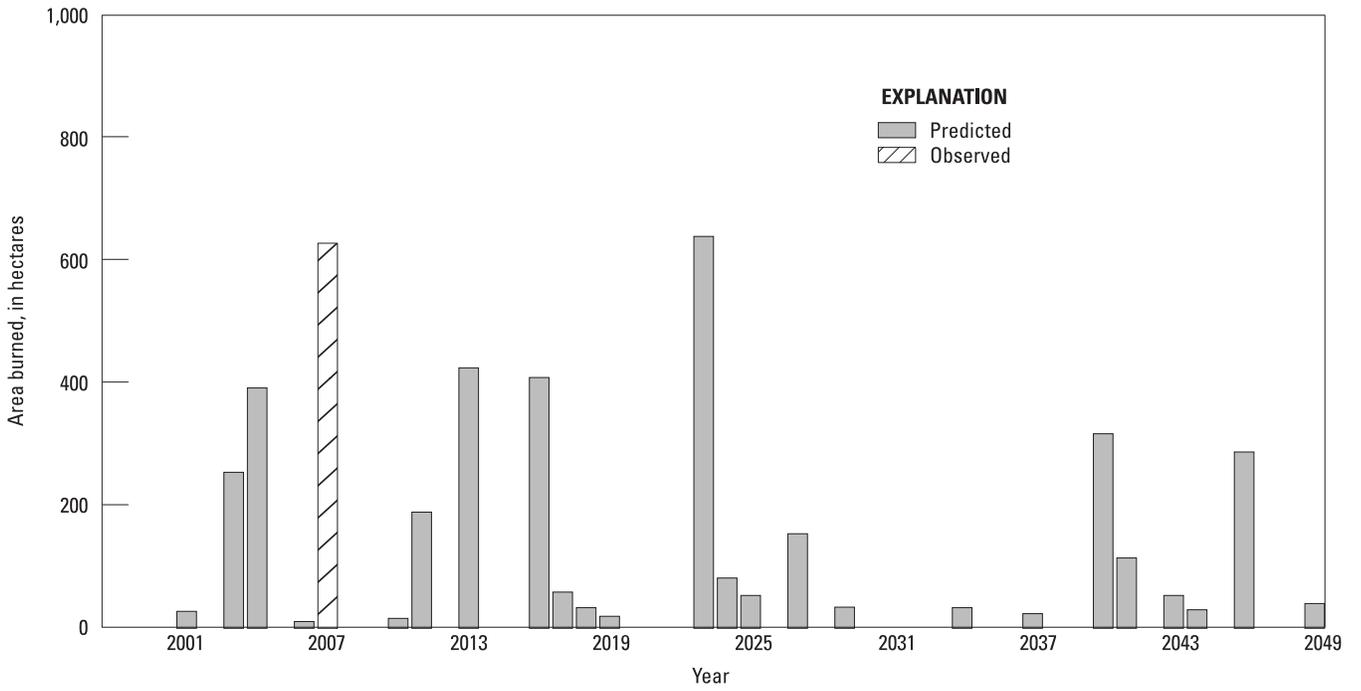
D

Figure 3.8.—Continued
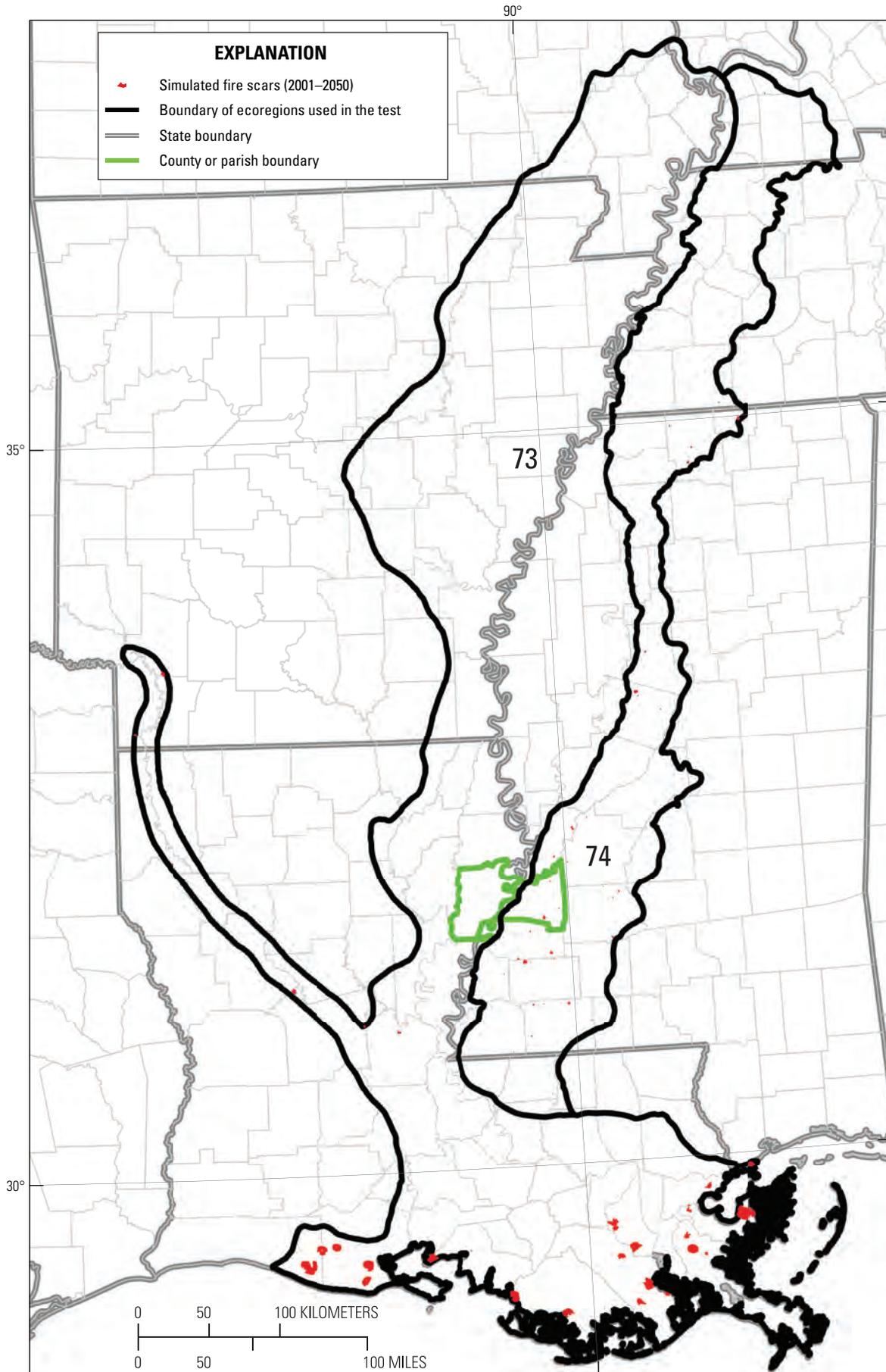
from beginning to end before moving to the next pixel. In an example linking GEMS with EDCM, a space-time sequence is used instead (each time step is simulated for the whole region before moving to the next step). This approach can be exploited to quantify lateral movements of water, soil, carbon, and 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 carbon 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 carbon 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 carbon 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

Figure 3.9 (facing page). 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). Although the largest scars are present in the Mississippi River delta area, scars are present throughout both ecoregions, but are too small to be shown at the scale of publication. Ecoregions are as follows: 73, Mississippi Alluvial Plain; 74, Mississippi Valley Loess Plains.

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 Grasslands/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 Grasslands/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 Grasslands/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 Grasslands/shrublands 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.

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 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 carbon 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 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 carbon 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

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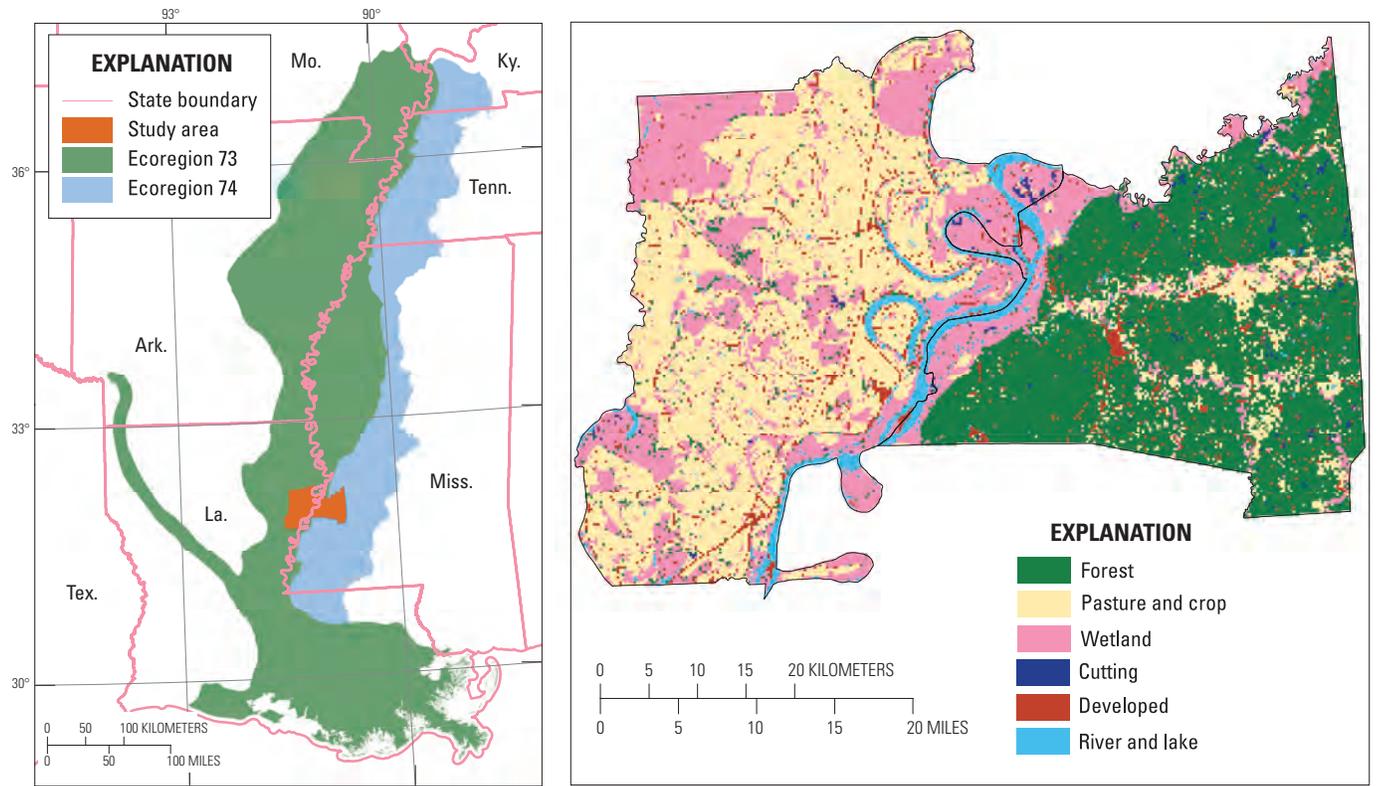
Figure 3.10.   Map showing study area for a test using terrestrial methods to assess carbon stocks, carbon sequestration, and greenhouse-gas fluxes. *A*, Location of test area. *B*, Distribution of land-cover classes in 2001. The test area includes Tensas Parish, La., and Claiborne County, Miss., in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

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 GEMS-spreadsheet method did not. Third, carbon sequestration in biomass decreased over time primarily because of the aging of forests in the region.
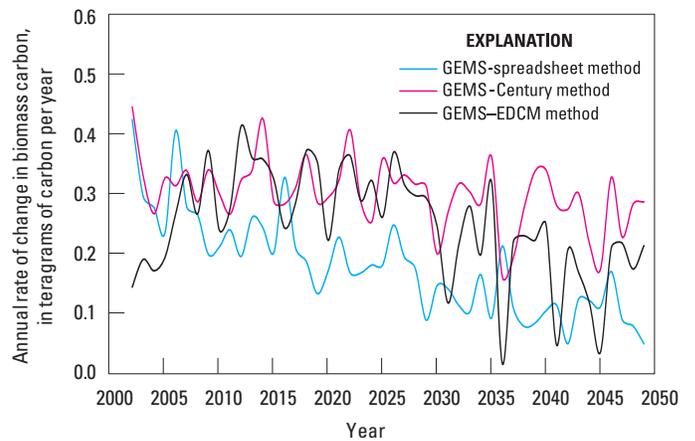
Figure 3.11.   Graph showing comparisons of annual carbon-sequestration rates of biomass carbon stock among the three methods (GEMS-spreadsheet, GEMS-Century, and GEMS–EDCM) using the "enhanced land use and land cover with reference land management" (L) scenario for the whole test area from 2001 to 2050. 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.

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) scenario.

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 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 contribution to the overall uncertainty. Using model ensembles within the GEMS framework, some of the model uncertainty can be reduced and the 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 emphasize

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$_2$O, nitrous oxide; R, "reference land use, land cover, and land management" scenario]

| Year | CH$_4$ from wetlands (billion grams of carbon per year) | | | | N$_2$O 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

A

B
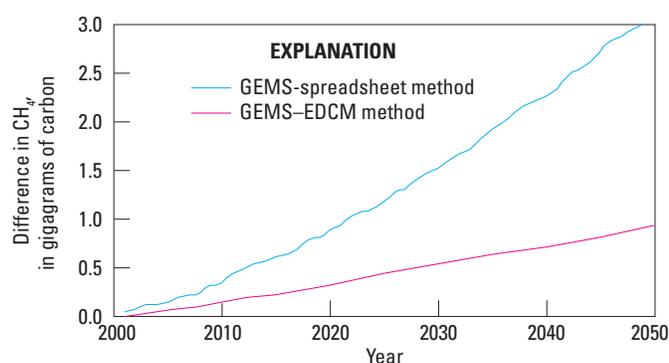
Figure 3.12.   Graphs showing comparisons of emissions between the GEMS-spreadsheet model and the GEMS–EDCM model, showing the difference between the "reference land use, land cover, and land management" (R) scenario and the "enhanced land use and land cover with reference land management" (L) scenario, from 2001 to 2050. The emission rate from the GEMS– EDCM model is the 10-year average. *A*, Annual methane emission from wetlands. *B*, Total annual nitrous-oxide emission from all land. Abbreviations and acronyms are as follows: CH$_4$, methane; EDCM, Erosion-Deposition-Carbon Model; GEMS, general ensemble modeling system; N$_2$O, nitrous oxide.
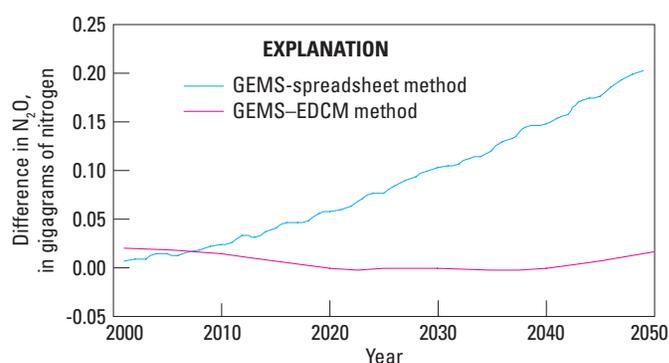
literature review and metadata analysis in order to quantify the uncertainty of field observations at the regional scale.

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 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

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[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.

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 a 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

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								

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 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.

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 service	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 and 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.

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:

$$ESCI = \frac{ES - ES_0}{ES_0},$$ (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/m²/yr), respectively, although the baseline value for 2001 through 2010 is 4.89 gC/m²/yr. An ESCI value of greater than zero indicates a positive increase in ecosystem service change compared to baseline (2001–2010); an ESCI value of less than

EXPLANATION

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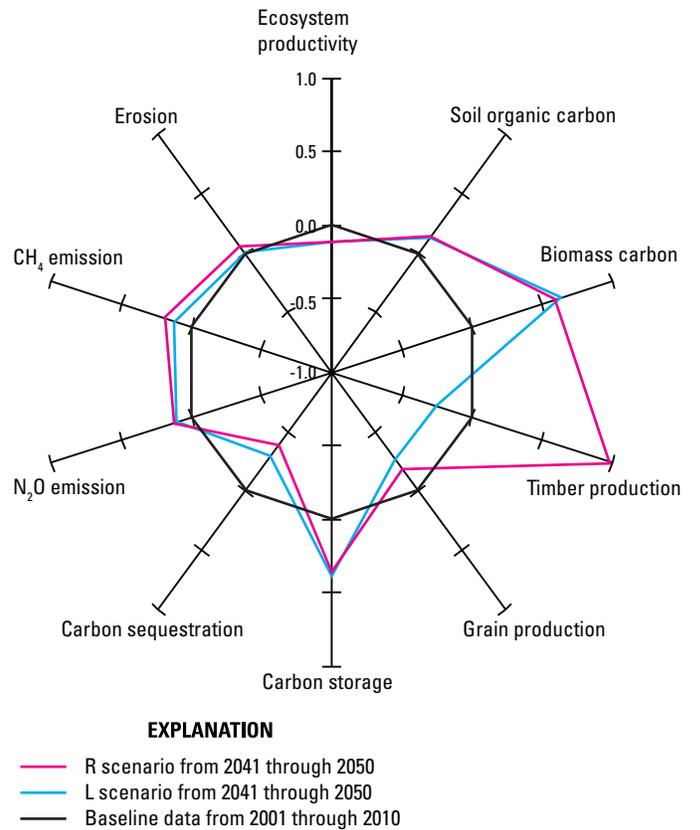
Figure 3.13.   Chart showing a comparison of ecosystem service changes using the ecosystem service change indicator (ESCI). Baseline data for 2001 through 2010 are shown along with projected changes from 2041 through 2050 using the "reference land use, land cover, and land management" (R) and the "enhanced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

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) Output value	R (2041–2050) ESCI	L (2041–2050) Output value	L (2041–2050) 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
Living biomass carbon	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

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 Huang and others (2004), Atkinson and others (2004), and Brown and Kadyszewski (2005). 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.

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

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 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: (1) identify, quantify, and document sources of error that underlie the assessment results; and (2) 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 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 others, 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 on the basis of IPCC guidelines on uncertainties (IPCC, 2006). Appendix G provides more detailed discussion.

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.

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 sources, 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.

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 carbon 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 3.17. A subset of primary deliverable or intermediate products for the national assessment.

[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; $MgCO_{2-eq}$/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	$MgCO_{2-eq}$/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 (N_2O, CH_4) reduction 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.
Updated and modified wildland fire perimeters and severity	Map series	Thematic classes	Annual for 2001–2010.
Projected modified 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.

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	Grasslands/shrublands	Wetlands	Aquatic ecosystems
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 requires cooperation and collaborations with more than one organization. Shared activities include 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 obtained 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 and bedrock geology).

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 ecosystems 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 ecosystems 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 Worldview2 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   General vegetative landscape or other types of surface cover, such as forests, grasslands, wetlands, or barren areas that can be mapped using remote-sensing techniques.

land mangement   In the context of this methodology and the subsequent assessment, refers to management decisions that

are applied to the use of land, such as frequency of forest cuts or amount of fertilization used in agriculture.

land use   In the context of this methodology and the subsequent assessment, refers to the use of land by humans, particularly the type or intensity of economic use of the land that changes attributes of the land cover, such as forest cuts or agricultural crop types, which can be mapped using remote-sensing techniques.

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.

methanogenesis   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.

Appendix A. Reference and Alternative Mitigation Scenarios

The reference and alternative mitigation scenarios will be designed to deliver results on the assessment components. (See chapter 1 for interpretation of the components and key concepts.) In essence, the components of the assessment required by section 712 of the Energy Independence and Security Act of 2007 (EISA) (U.S. Congress, 2007) will be satisfied by an evaluation of current carbon inventories, as well as potential carbon-sequestration capacity and greenhouse-gas (GHG) emission reductions from mitigation activities and strategies in ecosystems under a range of climate scenarios. The three overarching scenarios will be from the Intergovernmental Panel on Climate Change (IPCC) "Special Report on Emission Scenarios" (SRES)—A1B, A2, and B1 (Nakicenovic and others, 2000). The three IPCC scenarios are the socioeconomic storylines that will be used to guide the development of specific mitigation scenarios for this assessment. They are broad in scope and consistent with the IPCC SRES used in the U.S. Department of Agriculture (USDA) U.S. Forest Service's (USFS) 2010 Forest and Rangeland Renewable Resources Planning Act (RPA) assessment (U.S. Department of Agriculture, U.S. Forest Service, 2010b). The IPCC SRES storylines are derived from assumptions on global-level driving forces and need to be downscaled to the national and regional level. The role of the storylines is to push experts to think beyond present conditions and the current range of thinking.

For this assessment, reference and alternative scenarios for mitigation will be developed within each of the IPCC storylines. Reference scenario (R) and alternative mitigation scenarios in each assessment unit are developed for various socioeconomic storylines and climate scenarios. Alternative mitigation scenarios are designed to enhance carbon sequestration and reduce GHG emissions from land-management change (scenario M), land-use and land-cover change (scenario L), or both (scenario ML).

This appendix provides details on the national and regional processes to construct reference and alternative scenarios. At the national level, mitigation activities—such as land-use and land-cover (LULC) change and land-management changes—are selected for national assessment from a compilation of candidate mitigation activities. They are prioritized for national importance based on the existing knowledge of carbon-sequestration capacity, quantity of land suitable for the activity, and consulting agency priority. Ultimate inclusion of a mitigation activity in the assessment is determined by data availability and modeling capabilities. Also, national-level consultation will be used to develop a national set of storylines consistent with IPCC SRES and to establish guidelines for scenario construction to ensure consistency across ecoregion assessments. At the ecoregion level, reference scenarios (R) of LULC and land management are projected for each of the storylines within the confines of the national interpretation.

For each ecoregion, mitigation activities will be evaluated for the potential to maximize carbon sequestration and minimize GHG emissions; evaluations will use published studies, regional expertise, and spreadsheet calculations. Mitigation scenarios are portfolios of management activities and LULC changes described in terms of amounts of change and timing of implementation. In accordance with national guidelines, alternative mitigation scenarios will be constructed to enhance carbon sequestration. Further elaboration of mitigation-activity selection, interpretation of the IPCC storylines for the reference and mitigation scenarios, and scenario construction follows. The last section provides a summary of the national and regional consultation process.

A.1. National Selection of Mitigation Activities

The selection of mitigation activities for the national assessment involves prioritization of mitigation activities and identification of the relevant national datasets. The assessment addresses two types of mitigation activities that ecologically sequester carbon or mitigate GHG emissions in ecosystems: LULC change and land-management change. LULC change is described in terms of changes between thematic LULC classes (section 3.2 of the main document), and land management occurs within the confines of a LULC class. LULC changes for increasing carbon sequestration include afforestation (conversions from pasture and croplands into forested land classes), mine-land reclamation, and wetland restoration or construction (transitions into the wetland classes). LULC changes to reduce GHG emissions may include the reduction of deforestation and the reduction of rice cultivation. Management activities on croplands may include conservation tillage, more efficient fertilization application, and crop rotations. On forest lands, management pertains to forest management and timber harvesting. All these mitigation activities affect GHG fluxes from aquatic systems via effects on erosion and nutrient loads.

Candidate mitigation activities have been compiled from the literature (for example, Lewandrowski and others, 2004; Murray and others, 2005; Eggleston and others, 2006) and underwent preliminary preparation and review at a policy workshop that was conducted by the Center for Climate Strategies and convened at the U.S. Geological Survey (USGS) headquarters in Reston, Va., December 1–2, 2009. A catalog of mitigation activities was distributed in advance and participants provided feedback. Criteria to prioritize mitigation activities for national assessment may include the primary considerations for ecological carbon-sequestration capacity:

- Sequestration capacity per hectare of mitigation activity

- 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 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

The product of the first two measures recognizes activities that may result in smaller changes in rates of sequestration, but that are applicable to a vast quantity of lands (for example, rangelands). In addition, the priorities of consulting agencies will be considered in the selection of mitigation activities for the assessment.

Candidate mitigation activities listed in table 3.5 of this report are aligned with those incorporated into the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOM–GHG) (Murray and others, 2005) to provide perspective on the scope of the assessment and to indicate common areas where FASOM–GHG methods, data sources, and results for mitigation activities will be informative for the methodology (table A1). Not all FASOM–GHG mitigation strategies are within the scope of the assessment; for example, the category of fossil-fuel mitigation from crop and livestock production will not be used. Conversely, some mitigation activities not represented in FASOM–GHG are included as candidate mitigation activities in the assessment.

The mitigation activities will be researched before presentation to policymakers and the consulting agencies. The legislation requires the Secretary of the Interior to consult with the Secretary of Energy, the Secretary of Agriculture, the Administrator of the Environmental Protection Agency, the Secretary of Commerce (acting through the Under Secretary for Oceans and Atmosphere), and the heads of other relevant agencies. The candidate mitigation activities priorities will be discussed at a national workshop, but final selection will be subject to data availability, acceptance of assumptions, and model capabilities. Mitigation activities that currently are operational for the assessment are listed in table A2.

Land-use change is measured as the number of hectares of LULC class change. Within LULC classes, land-management activities are measured as the number of hectares of land-management change. Land management is complex because any one type of land management can be implemented with varying intensity. By way of example, Adams and others (1996, 2005) defined and used regional forest-management-intensity classes, ranging from passive to high-intensity management, for their analyses of carbon-sequestration supply. For the assessment, land management "carbon-sequestration intensity" relates to carbon-sequestration rate. For example,

carbon optimal harvests that maximize sequestration in the forest ecosystem and wood products are of greater "carbon-sequestration intensity" than economically optimal harvest rotations (Huang and Kronrad, 2001). Analogies for croplands include crop rotation (versus monocultures) and tillage intensity (Choi and Sohngen, 2009). Carbon intensities of grazing-land management will be framed by recent (2010) rangeland and grassland research (Follett and others, 2001; Bremer and Ham, 2010; Brown and others, 2010).

Also specified at the national level are guidelines to construct alternative mitigation scenarios that are portfolios of mitigation activities, with details on the amounts of change and the timing of implementation. At the regional level, three alternative mitigation scenarios are constructed relative to a reference scenario. The storylines behind each set of reference and alternative scenarios need to be interpreted at the national level to ensure consistency across ecoregions.

A.2. National Interpretation of Storylines

The next step toward creating a set of regional LULC and land-management scenarios is to develop a set of national storylines consistent with the IPCC SRES. This step will be done primarily through a national workshop. Using existing LULC projections associated with the IPCC SRES scenarios and other supporting data as a guide, expert opinions will be solicited to describe plausible reference scenarios of LULC and land management based on the underlying assumptions of the SRES storylines. National storylines can be viewed as thematically enriched sets of SRES storylines with characteristics specific to United States land use and land management. Nakicenovic and others (2000) provided the following narratives and assumptions for each of the SRES scenario families (table A3). For more complete descriptions of SRES storylines, see Nakicenovic and others (2000).

The A1B storyline and scenario family describes a future world of rapid economic growth, minimal or decreasing population growth, and the introduction of new and more efficient technologies. The primary underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per-capita income. The A1 scenario family develops into four groups that describe alternative technological changes in the energy system.

The A2 storyline and scenario family describes a heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge slowly, which results in population growth. Economic development primarily is regionally oriented, and per-capita economic growth and technological changes are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and

Table A1. Candidate mitigation activities compared with strategies associated with the Forest and Agriculture Sector Optimization Model with Greenhouse Gases.

[Modified from Murray and others (2005). FASOM–GHG, Forest and Agriculture Sector Optimization Model with Greenhouse Gases; CH_4, methane; N_2O, nitrous oxide; GHG, greenhouse gas]

Strategy/activity	Candidate mitigation activities	Mitigation activities tracked in FASOM–GHG
Afforestation carbon sequestration	Convert lands to forest[1]	Convert agricultural lands to forest.
Forest management carbon sequestration	Lengthen timber harvest-regeneration rotation Increase forest management intensity (increasing forest density, thinning, fire-fuel reduction, insect and disease management) Preserve forests[1]	Lengthen timber harvest-regeneration rotation. Increase forest management intensity. Preserve forests.
Forest management CH_4 and N_2O mitigation	Reduce deforestation[1]	Reduce deforestation.
Agricultural soil carbon sequestration	Reduce cropland tillage Crop mix change to high-residue crops Increase efficiency of crop fertilization Convert grasslands and perennial crops[1] Increase winter cover crops Reduce summer fallow Restore agricultural land Increase irrigation efficiency	Change crop tillage. Change crop mix. Change crop fertilization. Convert grassland.
Fossil-fuel mitigation from crop production		Change crop tillage. Change crop mix. Change crop input. Change irrigated/dry land mix.
Agricultural CH_4 and N_2O mitigation	Reduce cropland tillage Improve crop mix Increase efficiency of crop fertilization Reduce rice acreage[1]	Change crop tillage. Change crop mix. Change crop input. Change rice acreage. Change irrigated/dry land mix. Control enteric fermentation. Change livestock herd size. Change livestock system. Manage manure.
Grassland/rangeland soil carbon sequestration	Improve grazing management practices Restore degraded rangelands Improve use of fertilizer Allow natural succession towards native shrub and forest	Not applicable.[2]
Rangeland GHG mitigation	Reduce severe rangeland fire	Not applicable.
Grassland GHG mitigation	Avoid conversion to energy crops[1]	Not applicable.
Wetland carbon sequestration (negative impact on CH_4)	Preserve, construct, and restore wetlands[1]	Not applicable.
Wetland carbon mitigation	Preserve wetlands[1]	Not applicable.
Urban land carbon sequestration	Increase urban forests	Not applicable.
Barren land carbon sequestration	Reclaim mined lands[1]	Not applicable.
Wood product sequestration	Improve mill waste recovery Extend life of wood products Extend storage in landfills	Change wood product mix.
Wood product GHG mitigation	Improve logging	Not applicable.
Fossil-fuel mitigation	Not applicable	Produce crops for biofuel use.
Technological potential for carbon sequestration	Use biochar Restore degraded rangelands	Use biochar (under investigation).
Aquatic GHG mitigation	Reduce nutrient export from urban and agricultural lands Alter withdrawal from deep reservoirs	Not applicable.

[1]Indicates a land-use change in the assessment (as distinct from a land-management change).

[2]FASOM–GHG 2010 has expanded rangeland and grassland categories and therefore can track LULC changes in these categories, but no mitigation activities are currently implemented.

resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

A primary deliverable of the national workshop will be expanded LULC narratives and national-scale LULC trajectories. Nested within the national narratives will be assumptions on the regional variability of LULC and management where available (fig. A1). For example, a national-scale narrative might include assumptions on forest use while highlighting certain regions as likely places for changes in forestry.

In figure A1, the primary graph begins with the solid black line which denotes measured LULC change based on

the USGS Land Cover Trends project (Loveland and others, 2002). In this figure, the trends data represent national estimates for a hypothetical LULC class from 1970 to 2000. The subsequent pink line represents LULC composition as modeled using the "forecasting scenarios of land cover change" (FORE–SCE) model based on actual LULC measurements from the 2006 National Land Cover Database (NLCD) change product and LANDFIRE vegetation change tracker (VCT) products as inputs for 2001 through 2010. The set of three blue lines that follows represents hypothetical trajectories of the same LULC class for each of the scenarios in the IPCC SRES for the United States. The inset graph represents the spatial and temporal variability of LULC composition for the A1B SRES scenario across assessment units (U.S. Environmental Protection Agency's level II ecoregions, modified from Omernik (1987). The different colors represent discrete geographic regions.

Table A2.   Mitigation activities included in dataset of land-use and land-cover starting points.

[These mitigation activities have been implemented in simulation models proposed for use in this methodology. A discussion can be found in section 3.2 of this report. USGS EROS, U.S. Geological Survey Center for Earth Resources Observation and Science; USDA NASS, U.S. Department of Agriculture National Agricultural Statistics Service; USDA FIA, U.S. Department of Agriculture Forest Service Forest Inventory and Analysis Program; LANDFIRE, Landscape Fire and Resource Management Planning Tools]

Mitigation activity	Data source
Irrigation	USGS EROS National Irrigation Map.
Drainage	USGS EROS National Irrigation Map.
Fertilization	USDA NASS.
Residue management	Residue management county statistics.
Tillage	USDA NASS.
Crop rotation	USDA NASS.
Grazing	USDA NASS.
Manure application	USDA NASS.
Forest cutting	USDA FIA.
Forest thinning	USDA FIA.
Fuel treatments	LANDFIRE.

Table A3.   Qualitative characteristics associated with three scenario families from the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios.

[Modified from Nakicenovic and others (2000). GDP, gross domestic product]

Scenario characteristics	Special Report on Emission Scenarios storyline		
	A1B	A2	B1
Population growth	Low	High	Low.
GDP growth	Very high	Medium	High.
Energy use	Very high	High	Low.
Land-use changes	Low	Medium high	High.
Resource availability	Medium	Low	Low.
Pace and direction of technological change	Rapid	Slow	Medium.
Technological change favoring	Balanced	Regional	Efficiency and dematerialization.
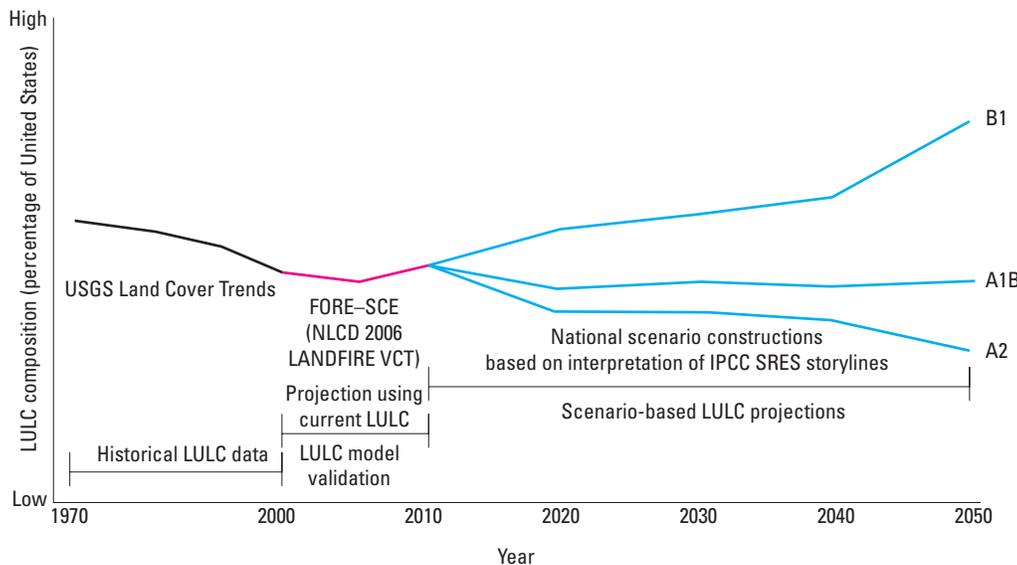
Figure A1.   Diagram showing the national and regional scenario scaling concept, showing past, present, and projected land-use and land-cover change. LULC, land use and land cover; FORE-SCE, Forecasting Scenarios for Future Land Cover model; NLCD, National Land Cover Database; LANDFIRE, Landscape Fire and Resource Management Planning Tools; VCT, vegetation change tracker; IPCC, Intergovernmental Panel on Climate Change; SRES, Special Report on Emission Scenarios.

A.3. Ecoregion Reference Scenario Construction

Regional reference scenarios build from the national storylines discussed above. The foundations of regional scenarios are LULC and land-management histories developed through review of existing historical data sources, including the comprehensive analysis of recent historical LULC change from the USGS Land Cover Trends research project (Loveland and others, 2002). Regional expert consultations will be used to project recent historical LULC into the future based on the current (2010) understanding of the interaction of drivers of LULC change. Regional experts will link SRES and national LULC and management storylines with the biophysical and socioeconomic characteristics of ecoregions to provide a range of LULC and management futures consistent with historical observations.

The scenario construction process also may incorporate exogenous projections of particular LULC types or management. Examples include projections of population from the U.S. Census Bureau or the USFS's 2010 RPA land-use projections; however, maintaining fidelity with the SRES storylines is required, and the regional expert consultation process will determine the degree to which these exogenous projections are used, if at all. Other coarse-scale LULC modeling efforts, such as those provided by IPCC SRES modeling teams, can be empirically downscaled and combined with existing expertise in LULC science, LULC histories reported in existing studies, and regional expert knowledge to construct regional LULC scenarios for each ecoregion. Constraints on scenario construction primarily are the SRES storylines and existing knowledge of regional LULC change. This flexible framework creates opportunities to explore a wide range of regional LULC scenarios, and remain consistent with overall SRES assumptions and characteristics.

A.4. National Interpretation of Storylines for Alternative Mitigation Scenarios

The interpretation of each national storyline is expanded to support the construction of the alternative mitigation scenarios. A mitigation scenario is a combination of future potential LULC and land-management changes (activities) associated with vetted climate and socioeconomic conditions to illustrate possible GHG mitigation capacities with various assumptions. There is no precedent for constructing alternative mitigation scenarios for the IPCC SRES. The USFS RPA assessment has not embarked on this endeavor. Alteration of each reference scenario to explore mitigation activities to enhance carbon sequestration and reduce GHG emissions compromises the internal consistency of the reference scenario that is devoid of carbon-sequestration policy. Notably, carbon-sequestration policy that leads to reduced GHG emissions and increased carbon sequestration affects climate, but this effect cannot be captured without modeling policy changes at the global scale. Although the more recent representative concentration pathways (RCP) effort (Moss and others, 2010) avoids this problem by finding alternative scenarios for each radiative forcing target, it requires scenarios to meet carbon sequestration and GHG-emission reduction targets, rather than explore ecosystem capacity. The methodology accepts climate incongruity for alternative scenarios. Conceptually, it is easier to guard each storyline for changes in land management (M), although changes in land management have implications for yields and consumption patterns. Departure from the storyline is exaggerated by LULC changes to enhance carbon sequestration (L and ML) because of competing uses for land to produce food, fiber, and energy for the population. The IPCC SRES storylines are used to motivate a diverse set of alternative mitigation scenarios emphasizing mitigation activities, different change amounts, and different concerns for the temporal aspects of carbon sequestration, including time-effectiveness and permanence of sequestration.

The three storylines are differentiated by assumptions that will be related to emphases on mitigation activities, amounts of change, and importance of timing and permanence of carbon sequestration. Examples are described below:

- For IPCC SRES storyline A1B—
  - The freeing of natural resources could enable afforestation
  - The emphasis on management versus conservation is more likely to promote plantations rather than natural forest
  - The pervasiveness of urban sprawl may restrict reductions in the rates of urban development
  - The technological progressiveness of A1B may justify technological feasibility of biochar and rangeland restoration
- For IPCC SRES storyline A2—
  - The increased or large population growth and focus on sustainable food production may limit conversion of agricultural lands to forest lands, but it may be compatible with agricultural practices that enhance carbon sequestration through conservation tillage, efficient fertilizer usage, crop rotations, and cover crops
  - The concern for water quality for sustainable agriculture may prompt wetland restoration
- For IPCC SRES storyline B1—
  - The focus on sustainable development may embrace sustainable food production and wetland protection within A2, but it also may include sustainable forestry practices including the following:
    - Afforestation and avoidance of deforestation
    - Expansion of urban forests
    - Forest management for carbon sequestration
    - Native species

◦ Resource efficiency may promote slower rates of development and increased urban density

◦ The sustainable development focus may value long- and short-term carbon-sequestration activities

Alternatively, proposals for national initiatives, similar to Conservation Reserve Program (CRP), for ecological carbon sequestration will be invited from consulting agencies and applied to varying degrees (for example, high, medium, and low levels of national commitment) across the storylines. Either way, the national consultation process will be relied upon to provide national bounds on increases in mitigation activities. Similarly, bounds on mitigation activities in ecoregions also need to be evaluated.

A.5. Ecoregion Evaluation of Mitigation Activities

For each ecoregion, mitigation activities will be examined for relevance (for example, grazing-land management is more prevalent in some ecoregions than others) and evaluated for their potential to sequester carbon and reduce GHG emissions. Evaluating LULC conversions and land-management changes in the ecoregion will identify activities that maximize carbon sequestration to provide an efficient means to construct alternative mitigation scenarios that "optimize" sequestration in the ecoregion given a limited number of scenario simulation runs and no iteration. Furthermore, a transparent evaluation of mitigation activities complements the complex simulations of LULC change and biogeochemical modeling. Evaluating mitigation activities is accomplished by using results from regional studies of carbon-sequestration-mitigation activities, consulting with regional experts (for example, GRACEnet participants), and developing a spreadsheet tool. Two objectives of GRACEnet are to identify an agricultural system that most likely maximizes soil carbon sequestration and to identify an agricultural system that minimizes net global warming potential (Jawson and others, 2005; U.S. Department of Agriculture, Agricultural Research Service, 2010). As a result of carbon-sequestration research, some regional studies of mitigation activities are readily available. For example, relevant studies about mitigation activities in the Mississippi Alluvial Plain and Mississippi Valley Loess Plains ecoregions include the following:

- Loblolly pine harvest rotations (Huang and Kronrad, 2006; Sohngen and Brown, 2008)

- Fertilization of loblolly pine plantations (Fox and others, 2007)

- Sequestration from softwood (evergreen) forest versus hardwood (deciduous) forest (Sohngen and Brown, 2006)

- Reforestation of poorly stocked pine plantation (Huang and others, 2004)

- Conservation tillage (Franzluebbers, 2005)

- Cotton rotations including pasture (versus monoculture) and with cover crops (Causarano and others, 2006)

- Restoration of bottomland forests (Wainger and King, 2001; Jenkins and others, 2009)

These studies provide details on potential land-management and LULC change for the ecoregion. State climate-change studies provide further indications of the potential to enhance sequestration. For example, the Arkansas Governor's Commission on Global Warming plan sets a target of 4 percent increase in urban trees by 2025 (Arkansas Governor's Commission on Global Warming, 2008). Consulting with regional experts will further develop a knowledge base for mitigation-activity potential to enhance sequestration capacity in the ecoregion.

A spreadsheet tool will be used to synthesize available study results and fill in details on carbon sequestration. The tool will present aggregated planning-level estimates of how annual rates of carbon sequestration and cumulative carbon sequestration will change with time as a result of changes in LULC and management from time of implementation. (This is in contrast to the reference and alternative scenarios that stage the implementation of the mitigation activities with time.) The spreadsheet tool will enable exploration of the sensitivity of carbon sequestration to forest management (thinning, harvest rotation, and sequestration in wood products) and agricultural crop rotations of importance to the ecoregion, as needed. A similar spreadsheet tool was developed for the U.S. Environmental Protection Agency (EPA) in the late 1990s and implemented for Omernik's (1987) ecoregions (Dennis King, University of Maryland, written commun., 2010). The Natural Capital Research Group at the University of Maryland Center for Environmental Science (UMCES) developed a spreadsheet approach during 1996 and 1997 for the EPA Office of Policy Analysis, in preparation for the 1997 Kyoto Conference. When the United States pulled out of the Kyoto negotiations in 1998, the project was suspended; the spreadsheet results for 22 management activities were not published, although they were used in 1999 and 2000 in a project for the EPA Office of Air to show how one might "score" domestic carbon trading that involved land-based carbon sequestration. Although this tool needs updating, further development, and refinement for the assessment, the effort provides a proof of concept.

The mitigation-activity spreadsheet tool will be developed to report results for each of the assessment units with calculations made at the regional and subregional levels. Each spreadsheet will show the expected change (gains, losses, and net) in carbon sequestration resulting from a specific LULC or management activity to another during three periods: a transitional term of 15 years, the medium term of 16 to 40 years, and the longer term of 41 to 100 years, or to an endpoint deemed appropriate for the mitigation activity (as the capacity of some forest ecosystems to sequester carbon is not captured within the 40-year horizon of the assessment). The results will be backed up by detailed tables showing how aboveground, belowground, and on-ground carbon is expected to increase and decrease with time. The spreadsheets will refer to the models that generated them (for example, the Century model from Parton and others (1993)), so that users interested in moving beyond planning-level estimates to consider specific policies in specific jurisdictional boundaries will have access to more detailed and precise numbers.

A column for hectares of suitable or available land for each mitigation activity will be inserted to complete estimates of total carbon potential for the activity and to provide an upper bound on change amount. Designating and bounding suitability is not a well-defined task. The FASOM–GHG conversion (for example, pasture to forest) suitability was derived from Natural Resources Conservation Service (NRCS) land surveys and expert opinion (Adams and others, 1996). The FORE–SCE probability surfaces indicate relative suitability of land for LULC. There are limits on land-management suitability, as well. For example, the benefit of no-till methods in heavy clay soils is questionable (Rochette and others, 2008).

A concept related to suitability is availability, which is the supply of hectares of mitigation activities for a price (Brown and Kadyszewski, 2005); therefore, suitability also is indicated by the hectares of mitigation activities supplied at a high carbon price. In short, various data sources and model results provide indications of hectares of suitability and availability; for the prototype study region, the availability of bottomland forest was taken from the marginal land analysis of Wainger and King (2001). The percentage change in bottomland forest was noted to fall within the percentage change of national afforestation estimated by FASOM–GHG for the $50-per-tonne (megagram) price (Murray and others, 2005) and the USDA (Lewandrowski, 2004). Similarly, the national results from the latter two studies were used to indicate conservation tillage change bounds, but regional results from those studies could be accessed for the assessment. The increase in urban forests was adopted from the State climate-change plans. Regional consultation also will be used to indicate bounds on the suitability and availability of hectares for mitigation activities in the ecoregion.

The assessment unit spreadsheets for mitigation activities will be populated as follows:

1. Available studies and regional subject expertise will be used to specify the mitigation activities for each LULC class in the assessment unit.

2. The Carbon Online Estimator (COLE; U.S. Department of Agriculture, U.S. Forest Service, 2010a), the Voluntary Reporting of Greenhouse Gases-Carbon Management Evaluation Tool (COMET–VR; U.S. Department of Agriculture, Natural Resources Conservation Service, 2010), and the Century carbon model (which has a user-friendly interface) will be used to estimate annual rates of carbon sequestration for each LULC and management activity within each EPA level II ecoregion from year 1 (for example, year of transition to the management activity intensity) to year 40 and beyond as appropriate.

3. The results of step 2 will be compared with results of earlier nationwide research (for example, Sperow and others, 2003).

4. The number of hectares in each LULC class and land-management carbon-intensity class for the starting conditions for each EPA level II ecoregion (section 3.2 of this report) will be obtained.

5. The hectares of LULC class suitability will be estimated using FORE–SCE probability surfaces, estimates from other studies (for example, FASOM–GHG suitability estimates based on data from the National Resources Inventory (NRI) of the NRCS), and regional consultation, as will land-management suitability limits.

6. A spreadsheet tool for each EPA level II ecoregion will be prepared (see table A4 for a sample report).

7. Instructions and caveats about using the spreadsheet data, providing explanations about how spreadsheet numbers were generated, and links back to underlying simulations and models will be documented.

Table A4. Sample spreadsheet format adapted from earlier spreadsheets for the U.S. Environmental Protection Agency.

[GHG, greenhouse gas; LULC, land use and land cover; Mg/ha/yr, megagram (metric ton) per hectare per year]

Ecoregion 1	From agriculture, croplands, harvested, conventional tillage, no cover crops	Hectares of mitigation activity		Carbon sequestration rate from "no change" (Mg/ha/yr)				Other GHG emissions
		Starting	Suitable	Years 1–15	Years 16–40	Years 41–100	Years 1–40	
LULC class	To							
Agriculture, croplands, harvested	Conventional tillage, no cover crops							
	Conventional tillage, cover crops							
	Conservation tillage, no cover crops							
	Conservation tillage, cover crops							
Agriculture, croplands, idle	Agriculture, permanent grass							
	Agriculture, wetlands							
Deciduous forest	Deciduous, 0–15 years							
Evergreen forest	Evergreen, 0–15 years							
Pasture/rangeland	Pasture/rangeland, herbaceous							

For users outside of the assessment, additional steps can be implemented to refine a spreadsheet tool to organize information for various spatial scales, such as counties and States, and to package spreadsheet tools in various ways to support the needs of users.

A.6. Alternative Mitigation Scenario Construction for Ecoregions

For an ecoregion, three alternative mitigation scenarios will be constructed to enhance carbon sequestration and reduce GHG emissions through land management (M), LULC change (L), and both (ML) for each storyline. Each set of storyline alternative mitigation scenarios will be built from national guidelines regarding mitigation activity emphases (for example, managed versus natural), commitments to change (for example, high, medium,

low), and aggressiveness of carbon sequestration (for example, urgent, constant, delayed). The evaluation of the mitigation activities, described above, provides the means by which to specify mitigation activities that maximize carbon sequestration, to bound mitigation activity change within the ecoregion and storyline, and to indicate carbon sequestration with time.

In the absence of national and regional consultation, a preliminary example of an alternative mitigation scenario for the sample region is provided for illustrative purposes in table A5. The features of an alternative enhanced scenario (for example, ML scenario for the A1B storyline (denoted as A1B_ML)) are as follows:

- Net change from 2010 to 2050 of the alternative scenario reported against the net change of the reference case

- LULC change implemented at an annualized rate of the net change (constant implementation)

Table A5a.   Reference A1B_R and alternative scenario A1B_ML for Mississippi Alluvial Plain.

[km², square kilometers; lbs/acre, pounds per acre (multiply by 1.12 to obtain kilograms/hectare); LULC, land use and land cover; N, nitrogen; P, phosphorus]

LULC class	2010 LULC (km²)	A1B_R net change 2010–2050 (percent LULC class)	A1B_L net change 2010–2050 (percent LULC class)	2050: A1B_L-R (km²)	LULC change comments/ directions	Land management change comments/directions
Water	13,396	10.8	10.8	0	No reduction in coastal wetlands	
Developed	9,855	12.9	12.9	0	No reduction in development (urban sprawl), no conversion of wetland to developed	Increase urban forestry: five trees per capita over next 15 years.
Barren	251	-1.6	-1.6	0	Mostly sand, not suitable for sequestration activities	
Mining	6	-3.9	-3.9	0	Mine lands ignored because of small size of area	
Mechanically disturbed	140	0.5	-48.8	-69	Reduced by doubling harvest rotation (with thinning)	
Fire disturbed	4	0.0	0.0	0	Forest-fire management maintains disturbance despite afforestation	
Deciduous forest	2,826	-16.5	-16.5	0	Reduce deforestation	
Evergreen forest	2,272	0.2	32.2	728	Favor plantations	Increase stock on understocked land. Fertilize at planting: 200 lbs/acre N and 25 lbs/acre P.
Mixed forest	1,505	-17.6	-17.6	0	Reduce deforestation	
Shrub/scrub	0	0.0	0.0	0		
Grassland	0	0.0	0.0	0		
Hay/pasture	4,352	12.1	6.1	-264	Reduce the R scenario increase in pasture for conversions to bottomland forest restoration / Increase pasture/crop rotations by 10 percent	
Row crops	62,620	-2.4	-16.4	-8,767	Conversions of marginal croplands to bottomland forest restoration / Increase pasture/crop rotations by 10 percent	Implement conservation tillage up to 50 percent of cropland. Implement wheat cover crop on 50 percent of cotton acreage. Increase cotton-soybean crop rotations (to reduce monocultures). Reduce rice acreage by 50 percent.
Woody wetlands	27,048	-1.9	29.1	8,372	Restore 2 million acres of bottomland forest	
Herbaceous wetlands	8,191	-6.1	-6.1	0	Avoid conversion of wetland to developed	
Total	132,468	no change	no change	0		

- Reasons for and amounts of LULC changes, and constraints on conversions
- Reasons for and amounts of land-management changes within LULC classes

Supporting references for each of the two types of mitigation activities in these ecoregions were noted in section A.2. Except for bottomland forest restoration in the Mississippi Alluvial Plain (where a study proposed acres of conversion), land-use percentages and management change are fabricated in the absence of a functioning regional consultation process.

There are many other factors that affect realized sequestration capacity including cost, technological feasibility, effects on ecosystem functions and services, energy usage, and policy implementation. The primary purpose of the scenario construction is to assess the ecological sequestration capacity of ecosystems. Demonstrating relations between carbon

sequestration and other factors are provided in chapter 3 of this report and appendix F.

A.7. National and Regional Consultation Processes

A.7.1. Framework for Engaging Expert Opinion to Calibrate Models

An important conceptual component of the modeling process is consultation. The goal of this consultation process is to ensure that the constituents of the reference and alternative mitigation scenarios being modeled in the assessment are relevant at the scale of the assessment unit. Further, it is desirable, and indeed necessary, that the processes and assumptions used to construct scenarios (and constituents)

Table A5b. Alternative scenario A1B_ML for Mississippi Valley Loess Plains.

[km², square kilometers; lbs/acre, pounds per acre (multiply by 1.12 to obtain kilograms/hectare); LULC, land use and land cover; N, nitrogen; P, phosphorus]

LULC class	2010 LULC (km²)	A1B_R net change 2010–2050 (percent LULC class)	A1B_L net change 2010–2050 (percent LULC class)	2050: A1B_L-R (km²)	LULC change comments/ directions	Land management change comments/directions
Water	562	26.3	26.3	0	No reduction in coastal wetlands	
Developed	4,998	38.8	38.8	0	No reduction in development (urban sprawl), no conversion of wetland to developed	Increase urban forestry: five trees per capita over next 15 years.
Barren	72	0.0	0.0	0	Mostly sand, not suitable for sequestration activities	
Mining	16	-11.1	-11.1	0	Mine lands ignored because of small size of area	
Mechanically disturbed	424	0.5	-49.6	-213	Reduced from doubling harvest rotations (with thinning)	
Fire disturbed	3	0.0	0.0	0	Forest-fire management maintains disturbance despite afforestation	
Deciduous forest	11,379	2.0	2.0	0	Reduce deforestation	
Evergreen forest	4,831	20.6	33.9	641	Favor plantations	Increase stock on understocked land. Fertilize at planting: 200 lbs/acre N and 25 lbs/acre P.
Mixed forest	4,681	3.4	3.4	0	Reduce deforestation	
Shrub/scrub	0	0.0	0.0	0		
Grassland	0	0.0	0.0	0		
Hay/pasture	5,008	-35.5	-35.5	0	Increase pasture/crop rotations by 10 percent	
Row crops	9,536	-15.2	-22.1	-661	Increase pasture/crop rotations by 10 percent	Implement conservation tillage up to 50 percent of cropland. Implement wheat cover crop on 50 percent of cotton acreage. Increase cotton-soybean-crop rotations (to reduce monocultures). Reduce rice acreage by 50 percent.
Woody wetlands	4,065	-5.7	0.0	233	Prevent further loss of woody wetlands, no study found to support restoration of woody wetlands	
Herbaceous wetlands	328	-1.4	-1.4	0	Avoid conversion of wetland to developed	
Total	45,903	no change	no change	0		

are consistent across ecoregions so that comparisons are valid. The assessment will engage regional experts to ensure regional relevance operating within a national framework to ensure consistency.

The assessment requires the integration of somewhat disparate models and project components, and consequent fields of expertise, such as LULC change, land-management change, biogeochemical modeling, policy, and economics. As such, the approach to calibrating modeling components will be split into two branches (fig. A2). One branch of the calibration process will focus on reference scenario development; the other will focus on mitigation scenario development. The two calibration branches are not independent, but can proceed in parallel with careful scheduling. Each of the two branches will be led by a subgroup in the assessment; the subgroup members will maintain contact with the other subgroup through the project leadership group. To improve the efficiency and outcomes of the calibration process, external organizations with significant experience in working with experts may be retained and used to help develop protocols, materials, and tools where needed.

An important aspect to all scales of scenario construction is the use of historical LULC, rates of LULC change, land-management dynamics, and other related data, both spatial and nonspatial. Examples of such data are found in table A6. These data will first be used during national reference scenario construction and consultation to document the historical trajectories of variables affecting U.S. LULC change and management, inform experts about spatial variability of U.S. LULC change, and provide a historical baseline from which to project changes in LULC and management under alternative scenarios.

A.7.2. National Reference Scenario Development (Box A in Figure A2)

The foundation of the assessment process is a suite of SRES-based reference scenarios. The three SRES scenarios will be interpreted, and a narrative description will be developed. These three scenarios form the basis for the national reference modeling scenarios. These national, initial "strawman" reference scenarios will be reviewed and refined by a wide array of relevant experts at a national workshop. Comments and suggestions from a geographically diverse set of workshop participants will be reviewed and incorporated where needed. The outcome of this process will be a set of national-level, reference storylines and scenarios. At this scale, focus
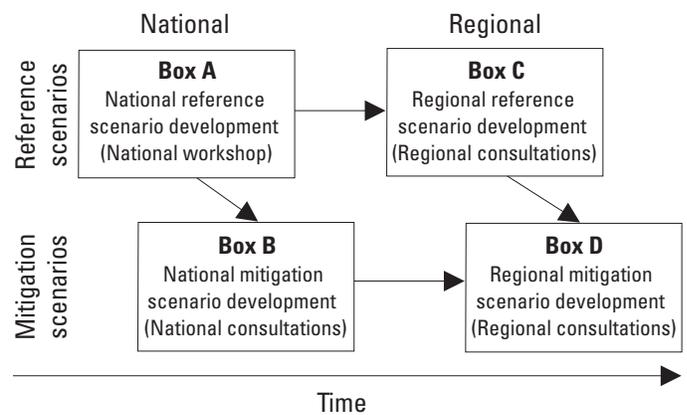
Figure A2.   Diagram showing the national and regional consultation process to obtain expert knowledge to calibrate scenarios for the assessment.

Table A6.   Data sources and characteristics used to inform and develop reference and alternative scenarios.

[USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey; LULC, land use and land cover; EPA, U.S. Environmental Protection Agency; NRCS, Natural Resources Conservation Service; m, meter]

Data source	Description	Spatial resolution	Temporal resolution
U.S. Population Census (U.S. Census Bureau)	Decadal population estimates, U.S. population projections	Subcounty (block, block group), county, State	10 years, with annual population projections.
USDA Census of Agriculture	Estimates of crop production	County, State	Every 5 years.
USDA Cropland Data Layer	State maps of crop type	30–60 m, States	Annual; 2000 to present (not national coverage).
USGS Land Cover Trends	Sample-based estimates of LULC change for conterminous United States; reports documenting LULC dynamics	EPA ecoregions (levels I, II, and III) and States	Every 6 to 8 years between 1973 and 2000.
National Land Cover Dataset and Database (NLCD)	Land-cover map of the conterminous United States	30 m	1992, 2000, 2006.
Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service	Sample-based point locations; characterizations of U.S. forest dynamics	Point-based observations on U.S. forest lands	Annual.
Protected Areas Database of the United States (PAD-US)	Polygons of protected areas of the United States	Feature-based; individual protected areas	Current; each feature has attributed data for establishment of area.
National Resources Inventory (NRI) of the NRCS	Sample-based estimates of land use and other changes (non-Federal lands)	Point-based estimates for States (some local and regional data/estimates also available)	1977, 1982, 1987, 1992, 1997.
National Wetlands Inventory (NWI)	Characterization of wetlands	Feature-based; local to national	Based on source data from 1980s and 1990s.

is on developing qualitative storylines rather than quantitative scenarios. The storylines will be the primary product used to develop regional land-use scenarios.

A.7.3. National Mitigation Scenario Development (Box B in Figure A2)

One of the key questions to be addressed for the assessment is which mitigation activities have the greatest potential to increase carbon sequestration and GHG fluxes. Because land-change modeling and biogeochemical assessment models are a central part of the methodology, the list of candidate mitigation activities must be compared against the capabilities of the models and data availability to ensure that they are compatible. A national consultation with a diverse set of experts will be used to obtain additional external review of the list of mitigation activities, prioritize mitigation activities for the assessment, set national guidelines for plausible maximum mitigation activity change, and provide guidelines on the assignment of mitigation activities to the storylines. Supplemental small meetings with specific relevant experts also may be held to ensure that a variety of stakeholder interest groups are represented. The outcome of this process will be a national set of guidelines for implementing mitigation scenarios to increase carbon sequestration and reduce GHG emissions at the regional level.

A.7.4. Regional Reference Scenario Development (Box C in Figure A2)

To improve the relevance of assessment results at regional levels, the national reference scenarios will be downscaled to EPA level II ecoregions (assessment units; modified from Omernik, 1987). To accomplish this important goal, a series of regional consultations will be conducted. Relevant assessment staff will identify and engage key experts in each ecoregion. Because many of the ecoregions are quite large, the team will explore using model input ranges based upon regional expert suggestions (for example, various data scales from the U.S. Census Bureau) with qualitative (for example, types of specific LULC transitions) and quantitative (for example, overall national rates of LULC change) constraints developed during the national scenario development stage to guide regional scenario construction. The results of this development process are a critical input to the next step in the process—developing regional-level mitigation scenarios.

A.7.5. Regional Mitigation Scenario Development (Box D in Figure A2)

Results from the national mitigation scenario workshop and regional reference scenario consultations are combined in this final step aimed at regionalizing mitigation scenarios. Regional experts will be engaged to work from a set of

activities from the national list in the context of the reference scenarios developed for that region. Regional engagement may be organized through regional entities such as the U.S. Fish and Wildlife Service Landscape Conservation Cooperatives (LCC) and the U.S. Department of Interior initiative for Climate Science Centers. Regional experts will suggest changes to the selected mitigation activities to improve local and regional relevance, will review the synthesis of relevant research and spreadsheet results, and will review three regional mitigation scenarios for each storyline. It is important to note that process consistency will be maintained throughout these steps by requiring that each successive scenario construction build upon previous stakeholder's or expert's calibration steps.

A.7.6. Schedule Considerations

The two branches of the calibration process interrelate, and careful scheduling of the workshops and consultations will be required to meet overall deadlines. It is important to remember that this calibration process is an early component of the overall production scheme, and delays in the calibration process will cascade down through the schedule and ultimately create delays in the final products. Adequate time for planning workshops and consultations, as well as compiling and interpreting the results, must be explicitly included in the calibration schedule.

The general process is as follows: national reference scenario development (box A in figure A2); national mitigation scenario development (box B in figure A2); regional reference scenario development (box C in figure A2); and regional mitigation scenario development (box D in figure A2); however, these steps are not necessarily sequential. Regional scenario calibrations must precede the corresponding regional mitigation strategy calibration, but the regional scenario calibrations can take place significantly earlier and do not need to proceed on a pace that matches the regional mitigation strategy calibrations.

A.7.7. Approximate Schedule

The approximate schedule is summarized below.

- The national reference scenario workshop likely will occur in fall 2010.

- National mitigation scenario workshop and consultations will follow as soon as the final results are available.

- Regional reference scenario consultations require products from the mitigation scenario workshop, therefore they cannot commence until the products are complete and the final results are available.

- Regional mitigation scenario consultations must follow the associated scenario consultation, and they should be completed for each ecoregion well before the products are needed by the modelers.

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Appendix B. Land-Use and Land-Cover Modeling

This appendix describes details of the spatially explicit land-use and land-cover (LULC) modeling component of this methodology. The simulation model FORE–SCE (forecasting scenarios of land cover change) will be used, which is a spatially explicit modeling framework that produces scenario-based, thematic LULC maps at annual time steps. The model begins with a LULC map representing conditions at the beginning of the simulation period and places realistic patches of LULC "change" for each subsequent yearly iteration. The proportion and type of LULC change are determined by the scenario being simulated, whereas the location of change is driven by site-specific biophysical characteristics. The modeling framework is capable of producing scenario-based simulations of future LULC change at a variety of spatial and thematic resolutions.

FORE–SCE originally was developed in support of a sensitivity analysis of the effects of LULC change on climate variability (Sohl and others, 2007; Sohl and Sayler, 2008). Although the initial application had specific requirements that helped define the initial model structure, the U.S. Geological Survey (USGS) modeling team designing FORE–SCE wanted to develop a flexible modeling system that could be adapted for future applications covering a range of research interests. FORE–SCE development began by adopting some of the key characteristics of the Conversion of Land Use and its Effects (CLUE) series of models (Veldkamp and Fresco, 1996; Verburg, Overmars, and others, 2006; Verburg, Rounsevell, and Veldkamp, 2006; Verburg and others, 2008). One of the primary components adopted from CLUE is the modular framework, with distinct but linked "Demand" and "Spatial Allocation" modules. This structure allows for both linkages with exogenous models, but also for direct or indirect incorporation of driving force factors operating at multiple scales. The flexibility offered by this framework greatly increases model utility for a variety of applications. What follows is an explanation of model design, potential data gaps, and primary outputs.

B.1. FORE–SCE Structure

B.1.1. Demand Component

The "Demand" component of FORE–SCE provides overall, regional proportions of LULC annual change (an annual regional "prescription" of LULC change). A wide variety of methodologies potentially can be used to construct demand, as long as the final products are simple tables of annual LULC change for each LULC class being mapped. Approaches used for construction of demand for past FORE–SCE applications consisted of extrapolations of historical trends (Sohl and others, 2007; Sohl and Sayler, 2008) and exploratory scenarios constructed through the use of expert knowledge (Sohl and others, 2007). CLUE modeling applications also have used trend extrapolations for demand (Verburg and others, 1999; Verburg, Overmars, and others, 2006), scenarios constructed through the use of empirical data and expert knowledge (Kok and Winograd, 2002), and complex modeling of demand through the use of a global economic model and an integrated assessment model (Verburg and others, 2008).

Demand for this application is directly linked to the use of storylines from the Intergovernmental Panel on Climate Change (IPCC) "Special Report on Emission Scenarios" (SRES) (Nakicenovic and others, 2000). Reference scenario demand will be provided by the scenario downscaling processes discussed in section 3.2 of this report ("Methodology Framework") and appendix A of this report ("Reference and Alternative Mitigation Scenarios"). Demand for alternative management scenarios associated with policy and mitigation actions will be provided by the methodologies discussed in section 3.2 of this report. Scenario-specific demand for reference and alternative scenarios will be provided as regionally specific prescriptions for annual LULC change from 2001 to 2050, with annual net change in individual LULC types. This information will be passed to the spatial allocation component of FORE–SCE, which will spatially distribute annual demand for change.

B.1.2. Spatial Allocation Component

The spatial allocation component of FORE–SCE ingests "demand" for a given region and spatially allocates prescribed LULC change on the landscape. The core drivers for identifying locations of LULC change are probability surfaces, constructed through the analysis of empirical relations between existing LULC patterns and a wide array of spatially explicit biophysical and socioeconomic data. Although the use of probability surfaces follows the primary methodology used by the CLUE series of models, the actual allocation of change is markedly different, with FORE–SCE utilizing a patch-based allocation methodology. The following provides a summary of the primary elements of the spatial allocation methodology.

B.1.2.1. Construction of Probability Surfaces

The spatial allocation component requires probability surfaces for each LULC class being modeled. Empirical analyses of the relation between spatial datasets representing drivers of LULC change and existing LULC patterns are used to construct the probability surfaces, using a stepwise logistic regression. The most stable and robust explanation for regional LULC patterns is obtained by analysis of endpoint (the most

current) LULC (de Koning and others, 1998); therefore, the dependent variable for use in the logistic regression analysis is the presence or absence of a given LULC type as mapped by the 2001 starting land-cover product (section 3.2 of this report). Independent variables used in the logistic regression include any spatially explicit datasets representing LULC driving forces.

Drivers of LULC change are unique and are based on geographic setting (Sohl and others, 2007). Given the unique characteristics of each region, probability surfaces will be independently modeled and constructed for each U.S. Environmental Protection Agency (EPA) level II ecoregion (modified from Omernik, 1987). For each ecoregion, driving-force variables linked to LULC change for that region will be identified, acquired, and formatted. Spatially and thematically stratified sample points are drawn from within an ecoregion, and values for land cover (dependent variable) and all ancillary datasets (independent variables) are extracted. Probability surfaces are then constructed for every thematic LULC class being modeled. For each LULC class, driving-force variables linked with the LULC class are identified, and an initial logistic regression run is performed. Initial results are examined for the presence of correlated independent variables. In cases where two highly correlated variables are selected by the stepwise regression, one of the two paired variables is discarded to mitigate the effects of multicollinearity. The regression is run again with the remaining variables. Output from the stepwise logistic regression is then used in the construction of probability-of-occurrence surfaces for that LULC class, as:

$$\theta_h = \left\{ 1 + \exp\left[-\alpha - \sum_{k=1}^{i} b_k x_{hk} \right] \right\}^{-1}, \qquad \text{(B1)}$$

where θ_h is the probability for pixel h being a member of the class (values range from 0 to 1);

α is the intercept parameter;

b is the regression coefficient for LULC class k; and

x is an explanatory variable.

The probability surfaces constructed from the logistic regression process are referred to as "baseline probability" and are a primary component of the remaining spatial allocation procedure as described below.

B.1.2.2. Model Parameterization

The FORE–SCE model relies on historical LULC data for parameterization of the spatial allocation component. Several key parameters governing FORE–SCE's patch-placement procedure use information from the USGS Land Cover Trends project (Loveland and others, 2002). As with the probability surface construction, model parameterization is done on an ecoregion-by-ecoregion basis. Before running the spatial allocation module, the following parameters are populated as follows: patch size, "clumpiness," probability modifier, and patch library.

Patch size.—Typical patches of LULC change differ in size and configuration, depending upon LULC type and region. For the patch-based spatial allocation procedure, patch-size distribution for every LULC type is required. Empirically measured patch sizes from the USGS Land Cover Trends project are analyzed for each LULC type. Mean patch size and standard deviation for every LULC type is used to populate tables for each ecoregion in the analysis area.

"Clumpiness."—Some forms of LULC change tend to occur as tightly collocated clumps, whereas other forms of LULC change tend to be more dispersed. A "clumpiness" parameter is used to control dispersion of LULC-change patches in the spatial allocation procedure. "Clumpiness" refers to the parts of the probability surface where change patches are allowed to be placed, and is expressed as a threshold value on the probability-surface histogram. For typically "clumped" LULC types such as urban and developed lands, the greatest probability values get preference for selection and placement of a change patch. For more dispersed LULC types, restrictions on the part of the probability histogram that can be used are more relaxed, resulting in more dispersed change patches. The "clumpiness" parameter for each LULC type is established through examining LULC change characteristics as mapped by the USGS Land Cover Trends project.

Probability modifier.—A probability modifier for a given LULC transition is based on scenario specifications and the likelihood of a given transition based on empirical historical data. Contingency tables from the USGS Land Cover Trends project provide a complete descriptive matrix of historical land-cover change for a given level II ecoregion, and thus provide historical context for the likelihood of a given LULC transition in that region. Scenario specifications also may have a strong effect on the potential likelihood of a given LULC transition. The USGS Land Cover Trends contingency tables and a scenario's unique specifications are used to construct probability-modifier tables for each ecoregion. Probability-modifier values range from 0 to 1 at 0.1 increments and simply are multipliers affecting the baseline probability surfaces (those constructed through the logistic regression procedure). For example, a probability modifier of "0" typically is assigned to all possible transitions of urban or developed land to another LULC type because these transitions are extremely unlikely, given the relative permanence of development on the landscape once it has occurred. As a multiplier to baseline probability, existing urban lands are thus excluded from potential change to another LULC type. A similar application of probability-modifier values can be used to alter baseline probability surfaces, reducing probabilities for specific forms of transition. Using the probability modifier is a powerful methodology for controlling specific scenario-defined storylines.

Patch library.—Patch size and distribution (through patch size and "clumpiness" parameters) are only two components affecting aggregate landscape pattern. Patch configuration and shape are another component. FORE–SCE mimics actual historical patches of landscape change to better represent landscape pattern. For each ecoregion, patch "libraries"

are populated for every LULC type by copying actual patch configurations (patches of a specific size, shape, and orientation) from the USGS Land Cover Trends database. The populated patch libraries are sorted by size, with multiple configurations for each patch size. The patch libraries are then used for the patch-by-patch spatial allocation procedure as discussed below.

B.1.2.3. Establishing Protected Areas

Although the probability surfaces define the suitability of a location to support a given LULC type, they do not account for the protected status of each parcel of land. The Protected Areas Database of the United States (PAD-US Partnership, 2009; for this methodology, the version of the database maintained by the Conservation Biology Institute of Oregon is used (PAD-US (CBI)) provides attributed polygons of protected lands in the United States. The PAD-US Partnership is a public and private collaboration to provide a database of public and private protected lands and includes Federal, State, and local protected lands, as well as information from national nonprofit organizations, such as The Nature Conservancy and Ducks Unlimited. Although it does not cover some protected lands, such as private conservation easements, the database does cover most of the protected lands in the United States. These data are used to better represent LULC change that may occur on these lands, with decision rules used to either alter or eliminate probabilities of LULC change occurring, dependent on the type of protection identified with each polygon.

B.1.2.4. Tracking Forest-Stand Age

FORE–SCE utilizes a forest-stand-age layer to establish and track the age of a stand of forest. This layer is used to mimic actual forest-cutting cycles and to inform the biogeochemical modeling on not only LULC type, but also the age structure of forested lands. Two sources of information are being used to construct an initial forest-stand-age layer. The vegetation change tracker (VCT) product (Huang and others, 2010) tracks disturbance using stacks of Landsat Thematic Mapper (TM) data. These data are being used to populate a database that identifies forest pixels disturbed between 1984 and 2001 and the date of last disturbance. In areas that have not been disturbed since 1984, an interpolated stand age surface is constructed from Forest Inventory and Analysis (FIA) sampling points. The "composite stand age" image constructed from these two sources will be used to track forest age as the model iterates through 2050.

B.1.2.5. Running the Spatial Allocation Component

The core of the spatial allocation module consists of the placement of individual patches of LULC change, guided by the aforementioned model parameterization and the regional probability surfaces. The process begins with the baseline probability surface for one of the LULC types being modeled. Patch placement is dependent on the combined characteristics of baseline probability, LULC type in the current iteration, the probability modifier parameter, decision rules on protected areas, and in the case of forest pixels, a function of current stand age. A "total probability" value is calculated for each pixel in the study area:

$$TPROB_{ij} = PROB_{ij} \times PROBABILITYMODIFIER_{ij} \times Function(PROTECTED) \times Function(HISTORY) \quad (B2)$$

where
$TPROB_{ij}$	is the total probability for LULC type i in ecoregion j;
$PROB_{ij}$	is the baseline probability for LULC type i in ecoregion j from the regression results;
$PROBABILITYMODIFIER_{ij}$	is the scenario-prescribed probability modifier for LULC type i in ecoregion j;
PROTECTED	are decision rules specific to the type of protected land; and
HISTORY	is the age since the last change in thematic LULC type.

The probability modifier is applied independently for every possible transition type in a given ecoregion. Probabilities within protected lands are altered according to decision rules specific for each form of protection. The HISTORY component is used to alter baseline probability for forest pixels, depending on when a pixel was last harvested.

Once total probability is calculated for a given LULC type, the "clumpiness" parameter is used to segment the probability-surface histogram into an "allowable" part for patch placement. To begin the patch-placement procedure, a stochastic methodology is used to place a "seed" pixel on the probability surface. A patch size then is assigned to the seed pixel. In past applications, patch-size distributions are represented

as Gaussian, an assumption that greatly simplifies the patch development process. A number generator capable of producing a random value within the desired Gaussian distribution is used to select a patch size based on the mean and standard deviation of patch sizes measured by the USGS Land Cover Trends project for that LULC type. The patch library for that LULC type is then consulted, and a random patch configuration for the assigned patch size is selected. The patch then is placed on the landscape.

The process is repeated for each LULC type, with the requisite number of patches placed on the landscape to meet areal "demand" for each LULC type. When demand is met, an LULC map is produced for that yearly iteration. Forest-stand-age maps are updated, with all undisturbed pixels iterated upwards by "1," and all disturbed (cut) forest pixels assigned a stand age of "0." The process then iterates forward to the next yearly iteration. At the start of each iteration, new probability surfaces are recalculated from updated, dynamic independent variables. For example, precipitation and temperature data will be used as independent variables in the logistic regressions, and if selected as predictor variables for a given LULC type, coefficients for the regression equation will be established. For future years, downscaled General Circulation Model (GCM) projections of precipitation and temperature will be used to update LULC probabilities, based on those changes in climate variables. Whereas some variables will remain static throughout the simulation period (for example, topographic variables), other variables associated with the changing landscape (for example, changes in urban development density) will be dynamic and will affect future probability surfaces.

Upon the completion of a modeling run, annual, thematic LULC maps from 2001 to 2050 will have been produced, consistent with the scenario-defined assumptions and resultant "demand" for each LULC type. Past applications of FORE–SCE have produced one set of maps for a scenario. For the national assessment, many model runs for each scenario will be produced. Given the stochastic components related to patch placement and configuration, using Monte Carlo simulations will allow for the examination of uncertainties associated with location of LULC change.

B.2. Land-Use and Land-Cover Modeling Components External to FORE–SCE

B.2.1. Coastal Modeling

The existing version of FORE–SCE is not equipped to deal with processes affecting coastal LULC change, especially coastal-wetland change in response to natural processes such as sea-level rise or erosion and deposition. Given the difficulties in specifically modeling all processes affecting LULC change, it is important that regional LULC models be able to use existing research and modeling activities where possible (Sohl and others, 2010). Rather than utilize FORE–SCE to loosely mimic coastal-change processes, an exogenous

coastal-process model will be used with modeling results separately integrated with FORE–SCE results.

Assumptions of static landscapes inspire predictions that about one-half of the world's coastal wetlands will disappear in response to acceleration in the rate of sea-level rise during this century. These estimates, however, incorrectly rely on models where bed surfaces accrete at historical rates, where inundation occurs across static landscapes, or on comparisons between historical accretion and future sea-level rise (Kirwan and Guntenspergen, 2009).

Coastal ecosystems are dynamic environments that have significant capacity to adjust to changes in rates of sea-level rise through nonlinear feedback mechanisms. These types of ecogeomorphic feedbacks likely explain the persistence of wetlands within the intertidal zone for thousands of years, as indicated by the stratigraphic record, and observations of accretion rates that are highest in regions with historically high rates of sea-level rise.

An ecogeomorphic model that incorporates nonlinear feedback among inundation, plant growth, and substrate accretion (Kirwan and Guntenspergen, 2010) will be used to project coastal-wetland change for the United States under different sea-level-rise scenarios. In this model, the marsh surface accretes at a rate determined by its elevation relative to sea level. Increasing inundation leads to higher rates of sediment deposition, which helps coastal wetlands keep pace with sea-level rise. Vegetation also responds to increasing inundation and vegetation growth increases at low elevations, enhancing sediment trapping and organic matter accretion and limiting erosion; however, the model also recognizes that there are limits to the conditions under which feedback between inundation and sediment accretion can maintain a stable intertidal system.

This model has been used in the first comprehensive attempt to model coastal-wetland resilience to accelerating sea-level rise. Our experiments indicate that a threshold rate of sea-level rise exists above which inundation leads to rapid and irreversible conversion of intertidal marshland into unvegetated subtidal surfaces. The specific site conditions (tidal range and suspended-sediment concentration) that respond to maximum rates of sea-level rise also were identified. The results indicate that the amount of sediment available for accretion strongly affects the maximum rate of sea-level rise that coastal wetlands can survive, a positive relation exists between the threshold rate of sea-level rise and tidal range, and interactions occur between tidal range and suspended sediment in the water column.

The predictions of threshold sea-level-rise rates for a large range of sediment concentrations and tidal ranges agree with observations from estuaries worldwide that were not used to design or parameterize the model. The results indicate that regions with low tide ranges or suspended-sediment concentrations will submerge in the near future, even for conservative projections of sea-level rise, and that marshes in high-tide-range environments with abundant sediment are likely to remain stable under more rapid projections of sea-level rise.

B.2.2. Integration With Disturbance Modeling

To better represent processes related to fire disturbance, insect damage, and other natural disturbances, an exogenous disturbance modeling effort will be used (section 3.3.3 in this report). Given the "competition" for land between the primarily anthropogenic change modeled by FORE–SCE and the primarily natural change modeled by the disturbance modeling, annual communication between the models is essential for the national assessment. At the start of a yearly iteration, the disturbance model will produce polygons of disturbance and pass those data to the FORE–SCE modeling environment. Those natural disturbance polygons will be directly used in that year's final LULC map and will be excluded for consideration for LULC change within the FORE–SCE modeling environment. The relation between natural disturbance and potential effects on probabilities for the anthropogenic LULC change tracked by the FORE–SCE model also will be examined.

B.3. Potential Data Gaps

LULC modelers must try to establish causality between LULC change and the biophysical and socioeconomic drivers of change; however, a primary difficulty in establishing those linkages is the availability of representative spatial data for those driving-force variables (Parker and others, 2002). Spatially explicit statistical models have been criticized for overreliance on datasets that happen to be available and underrepresentation of significant drivers of LULC change without easily obtained spatial data (Briassoulis, 2000). This uneven availability of the data remains an issue for spatial models that rely on logistic regression and the use of probability surfaces. Simply put, adequate data to represent all pertinent driving forces of LULC change often are not available. Although the outlined methodology and available data should successfully meet the goals of the assessment, LULC modeling potentially could be improved if land-ownership information, water-availability information, updated wetlands information, FIA data access, national VCT data, local zoning and regultory data, and data about dynamic independent variables were available. These data needs are summarized below.

Land-ownership information.—Individual land owners and resource managers make land-use decisions based on the constraints or opportunities afforded to them within their unique geographic and ecological setting (Sohl and others, 2010). Detailed land-ownership information at the national level would undoubtedly improve the ability to represent differences in land-use decisions between primary ownership groups. For example, shifts in ownership patterns in the Southeastern United States have the potential to dramatically alter forest structure in the region (Sohl and others, 2010). Both private industrial forestry and private nonindustrial forestry are altering the landscape significantly in the Southeastern United States, but there are major differences between the groups in land use and management. The capability is lacking to explicitly map and track land-management changes, as spatially explicit data on ownership at that level of thematic detail also are lacking. Because of the lack of ownership data, regional assumptions regarding land management across all ownership types are made.

Water-availability information.—Availability of groundwater or surface water has a tremendous effect on agricultural land use. Downscaled, projected climate data consistent with IPCC SRES storylines will be available for use by the land-cover modeling team, and projected precipitation changes will affect characteristics of probability surfaces used in the spatial allocation module; however, projected changes in surface water or groundwater that can be used as irrigation sources will not be used. Ideally, FORE–SCE would link with a comprehensive hydrologic model that is tied to water use and projected climate change for each IPCC scenario; however, the complexity and site-specific nature of hydrologic models that potentially could provide information on groundwater or surface-water changes prohibits their utilization at the national scale. There is no mechanism, therefore, by which to model changes in irrigated agriculture as a direct response to changes in water availability. The primary option in lieu of this information is to make informed estimates of projected future effects of future water availability at the regional scale, and to handle changes in irrigated agriculture through the top-down, "Demand" component of the LULC modeling (define future proportions of irrigated agriculture through the scenario construction process).

Updated wetlands information.—Wetlands are difficult to map through standard mapping methodologies relying on remote-sensing data. Dedicated, intensive interpretation efforts such as the National Wetlands Inventory (NWI) program are extremely valuable for providing consistent, accurate, and thematically detailed wetlands mapping. Two issues that potentially affect the ability to represent wetland extent are digital availability of products such as NWI for the entire Nation, and the date of wetland information and the lack of updating. A national wetlands layer for the National Spatial Data Infrastructure (NSDI) is being constructed, but as of late 2007, coverage was limited to 60 percent of the conterminous United States (U.S. Fish and Wildlife Service, 2007). The U.S. Fish and Wildlife stated two primary goals for the NSDI: (1) complete wetlands mapping for the Nation, and (2) explore ways to keep the national wetlands database populated with updated (current) information, while simultaneously acknowledging the practical considerations with regard to funding. A consistently updated wetlands layer for the NSDI likely would satisfy current and future needs of the national assessment.

Forest Inventory and Analysis (FIA) data access.—As discussed above, FIA data currently are used in conjunction with VCT data to produce a starting "forest-stand-age" surface. FIA data are used much more extensively by the biogeochemical modeling team. Given the privacy and dissemination issues associated with FIA data, data access remains a primary challenge.

National vegetation change tracker (VCT) data.—VCT data are used to populate an initial "forest cutting" class in the 2001 baseline land cover (section 3.2.1 of this report), as well as to produce an initial forest-stand-age surface. As of 2010, VCT data are not available at a national scale, as past VCT research has focused on prototype development, but plans are underway to produce these data at that scale. If timeline or other issues delay availability of VCT data for the national assessment, other data and methodologies will have to be used for mapping the initial forest-cutting class and the forest-stand-age surface.

Local zoning and regulatory data.—Urban development is a relatively small land use at the national scale, but LULC transitions to urban development typically are "one-way" transitions, with the land permanently removed from the pool of pixels available for LULC change (and also subsequently limited in the potential options for carbon sequestration and mitigation). The basic FORE–SCE design should provide realistic regional patterns of urban change, but because local zoning or regulatory information that may restrict or encourage urban development is not being used (apart from the PAD-US data discussed in the previous section), local accuracy may suffer. Availability and incorporation of nationally consistent zoning and regulatory information at the local scale would improve local accuracy of urban development; however, this is a minor issue at the national scale in terms of carbon-sequestration potential. It could potentially affect the ability to accurately portray local effects of LULC change on carbon and other ecosystem services.

Dynamic independent variables.—As mentioned previously, future climate projections are consistent with IPCC reference scenarios, and as the model iterates, neighborhood variables (for example, urban density) also will be updated to be used as independent variables for the logistic regressions. Future projected changes in many independent variables cannot be tracked or modeled. Some independent variables are relatively static and likely would not require updating (for example, topographic variables), but there are independent variables that are inherently dynamic and for which projected values through 2050 are not readily available. This limited availability limits the ability to examine LULC response to changes in these driving-force variables; however, trying to model processes governing all input independent variables is difficult.

B.4. FORE–SCE and Modeling Deliverables

LULC modeling deliverables include information and data related to scenario-based LULC forecasts and the scenario framework and assumptions themselves. In summary, primary deliverables provided by the LULC modeling team will include the following:

- Initial (2001) land cover
- Initial (2001) land-use and land-management characteristics

- Narrative storylines for each of the "baseline" IPCC scenarios. Constructing national and regionally specific scenarios will include techniques for incorporating exogenous modeling results, historical LULC data, and the primary assumptions associated with each IPCC scenario. These data will be used to construct regionally specific scenarios consistent with IPCC assumptions. Narrative storylines will illustrate general expected effects of IPCC storylines on regional LULC change and can be used to communicate regionally specific driving forces of change

- Quantified scenarios ("Demand"), including LULC trends with time, land-management characteristics, and land-use histories

- Annual LULC for each "baseline" IPCC scenario through 2050, including maps of LULC and spatially explicit probability distributions resulting from Monte Carlo runs of the spatial allocation module

- Annual LULC for each "alternative" policy or mitigation scenario, including maps of LULC and spatially explicit probability distributions

- Land-use history information, including annual forest-stand age, for each "baseline" and "alternative" scenario

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Appendix C. Characterization and Modeling of Major Ecosystem Disturbances

The assessment of the Nation's ecosystems for biological carbon sequestration will explicitly address disturbances such as wildfires (resulting from natural causes and human activity), as required by section 712 of the Energy Independence and Security Act (EISA; U.S. Congress, 2007). The national assessment disturbance methodology also will include tornadoes, damaging winds, hurricanes, and insect and disease outbreaks (table C1). Additionally, management activities, such as fuel treatments, designed to affect disturbances also will be considered by the disturbance methodology. For each disturbance type or management activity, the national assessment will follow a similar series of steps (fig. C1). First, recent disturbance patterns will be characterized as the number of events and area affected each year by ecoregion. The characterizations of recent trends will then be used to identify relations with climate, biophysical, and anthropogenic variables using statistical methods. When the resulting relations are statistically significant and ecologically relevant, they will be used to project future disturbance patterns.

The characterization of recent trends and statistical relations will capture broad-scale patterns, but additional methods are needed when projecting to locate and simulate the effects of each individual disturbance event; therefore, the national assessment will incorporate a second suite of methods to simulate the spread or placement of individual disturbance events at the pixel level when possible. These components of the disturbance model will include fire spread, empirical wind-fields, and habitat-suitability models for insects and disease. Some disturbances, especially insects and diseases, will lack the data or ecological understanding needed to build predictive relations at the 30-meter (m) pixel scale. In these cases, the summaries of recent disturbances and projections will be used to provide ecoregion-level disturbance probability distributions to the biogeochemical model (appendix D of this report), which will incorporate the spatial uncertainty inherent to the ecoregion-scale probabilities. The disturbance modeling will be adaptive and will incorporate new scientific understanding, data, and methods as they become available during the national assessment.
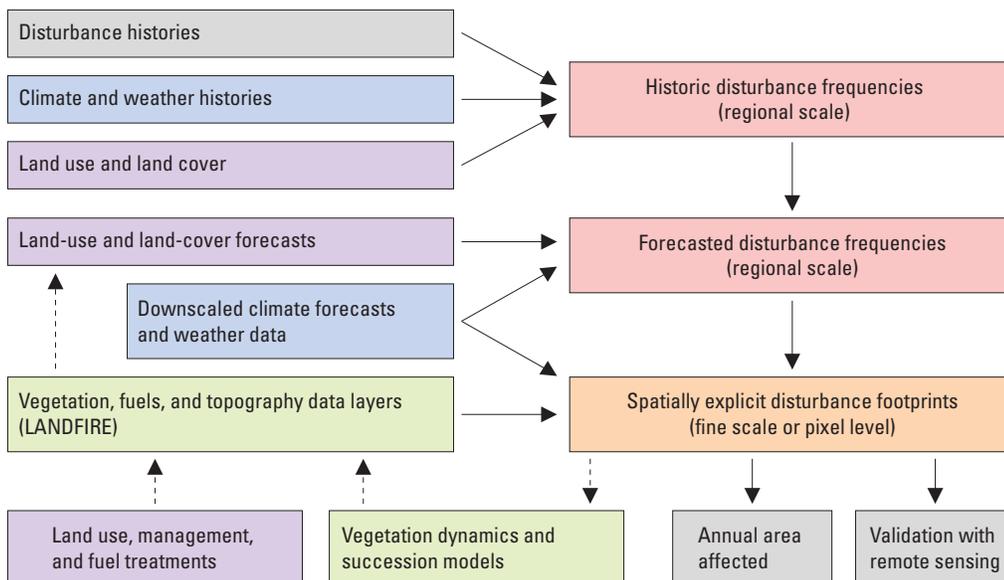
Figure C1. Generalized process and data flowchart showing disturbance modeling component tasks. Solid lines represent processes linking input datasets, models, and output datasets. Dashed lines indicate processes that update data sources required for disturbance modeling. Because each disturbance type differs in terms of the driving forces and the scales over which they operate, this streamlined modeling approach will be modified for each disturbance type. These distinctions will necessitate that the disturbance methodology be adaptive and include components that operate at different spatial and temporal scales.

C.1. Characterizing Past and Current Ecosystem Disturbances

C.1.1. Events Database

The national assessment will leverage the fire-disturbance data compiled and used to maintain the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) data products. Additionally, several key datasets, not currently (2010) utilized by LANDFIRE, will be incorporated to characterize past and current nonfire disturbances. An events database will be constructed to hold data describing major ecosystem disturbances from the LANDFIRE refresh data call; burn perimeter and severity data from Monitoring Trends in Burn Severity (MTBS) (Eidenshink and others, 2007); data describing insects and diseases from the Forest Health Monitoring (FHM) program of the U.S. Forest Service (USFS); data from the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center's hurricane archive; and data from NOAA's National Weather Service Storm Prediction Center tornado track and damaging wind event archives (table C1). Data from the National Fire Plan Operations and Reporting System (NFPORS) also will be incorporated into the events database to characterize fuel treatments (table C1).

For many disturbance types, the existing data incorporated into the events database will contain only point and line vector information. For example, hurricane, tornado, and damaging wind data consist of lines and points of the approximate storm locations; additional information is needed to characterize the area affected. Remote sensing of landscape change can help fill these information gaps. Dramatic vegetation changes, such as stand-replacing fires and forest clearcuts, are easily identified in imagery; however, less severe types of disturbances, such as insect outbreaks and storm damage, are more difficult to distinguish (Ahren, 1988; Franklin and others, 2003; Skakun and others, 2003; Kennedy and others, 2007; Vogelmann and others, 2009). Therefore, disturbed areas will be identified by using vegetation change-detection algorithms that (1) take advantage of the rich temporal information in Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) time-series stacks, and (2) search for anomalies in spectral reflectance and vegetation indices trends across all image dates (Huang and others, 2009, 2010).

The results of the vegetation change analysis will be used to augment the events database and provide additional data about the locations of fuel treatments, insect and disease outbreaks, and storm damage to vegetation; for instance, the FHM aerial-survey data are provided as polygons indicating disturbance cause, such as the mountain pine beetle. There is heterogeneity in disturbance severity within the FHM polygons—healthy trees are interspersed among unhealthy trees. This heterogeneity will be captured by assigning attribute information about the disturbance cause provided by the FHM polygons to disturbed areas identified by the vegetation change analysis. Similarly, disturbed patches in the imagery that are spatially coincident with storm locations would be attributed as storm damage.

Table C1. Summary of major ecosystem disturbances resulting from both natural causes and human activities, including disturbance-related management activities, to be assessed for effects on carbon sequestration and greenhouse-gas fluxes, spatial resolution of disturbance forecasts, disturbance projections reported, input data sources, explanatory variables, and potential management options implemented under the reference and enhanced scenarios.

[m, meter; MTBS, Monitoring Trends in Burn Severity; LANDFIRE, Landscape Fire and Resource Management Planning Tools Project; NFPORS, National Fire Plan Operations and Reporting System; NOAA, National Oceanic and Atmospheric Administration; RSLC, remote sensing of landscape change; USFS, U.S. Forest Service]

Disturbance type	Spatial scale	Attributes	Data sources	Broad-scale explanatory variables	Fine-scale explanatory variables	Scenario and management options
Wildland fires (human caused and natural)	250-m pixels	Fire size, severity, and emissions	MTBS LANDFIRE	Climate Land use Population	Weather Vegetation Topography Distance from urban area	Active fire suppression.
Fuel treatments (including prescribed fires)	250-m pixels	Areas and types of treatment	NFPORS LANDFIRE		Vegetation Land ownership	Increased or decreased number and area of treatments.
Hurricanes, tornadoes, damaging winds	250-m pixels	Storm tracks and areas of mortality	NOAA RSLC		Vegetation Topography	
Insects and diseases	250-m pixels	Areas of defoliation and mortality	USFS Forest Health Monitoring Aerial Surveys RSLC	Climate Past outbreaks	Climate Vegetation Topography Distance from previously affected areas	

C.1.2. Field-Reference Database

The field-reference database will be a compilation of all existing georeferenced field data available for the United States in the Fire Effects Monitoring and Inventory Protocol (FIREMON) database structure compiled for LANDFIRE. It includes Forest Inventory and Analysis (FIA) data from the USFS, fire monitoring data from the National Park Service, and data from the U.S. Geological Survey's Gap Analysis Program (GAP). Data will be acquired and compiled as the assessment progresses geographically across the Nation. Data in the field-reference database will be used to validate the disturbance and management information in the events database (section C.1.1 of this report).

C.1.3. Annual Summaries of Past and Current Disturbances

Using the disturbance data described above, participants in the national assessment will start by characterizing past disturbances into annual summaries 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 will include additional ecoregion-level estimates for emissions, and individual estimates for each fire calculated will be totaled 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 (modified from Omernik, 1987) (table C2).

C.2. Identifying Drivers of Ecosystem Disturbances

To project future disturbance events, the critical driving variables determining occurrence patterns need to be identified. Within the disturbance-modeling framework, these relations will be identified for ecoregions and for individual disturbance events. This two-scale approach will allow incorporation of broad-scale climatic drivers as well as fine-scale land-use, vegetation, and topographic patterns that affect individual disturbance events.

C.2.1. Ecoregion-Level Relations

The ecoregion annual disturbance summaries will be used to identify relations between disturbances and broad-scale climate, biophysical, and anthropogenic drivers using empirical methods. For example, interannual variability in fire

Table C2. Example of an output table showing recent disturbance summary data for the Mississippi Valley Loess Plains ecoregion.

[*n*, number of wildfires; MTBS, Monitoring Trends in Burn Severity]

Disturbance type	Year	*n*	Hectares	Source
Wildfire, human	1984	0	0	MTBS
Wildfire, human	1985	0	0	MTBS
Wildfire, human	1986	1	239	MTBS
Wildfire, human	1987	0	0	MTBS
Wildfire, human	1988	2	518	MTBS
Wildfire, human	1989	0	0	MTBS
Wildfire, human	1990	2	529	MTBS
Wildfire, human	1991	0	0	MTBS
Wildfire, human	1992	1	223	MTBS
Wildfire, human	1993	3	705	MTBS
Wildfire, human	1994	4	2,666	MTBS
Wildfire, human	1995	0	0	MTBS
Wildfire, human	1996	6	4,367	MTBS
Wildfire, human	1997	0	0	MTBS
Wildfire, human	1998	2	383	MTBS
Wildfire, human	1999	1	202	MTBS
Wildfire, human	2000	2	731	MTBS
Wildfire, human	2001	0	0	MTBS
Wildfire, human	2002	0	0	MTBS
Wildfire, human	2003	0	0	MTBS
Wildfire, human	2004	0	0	MTBS
Wildfire, human	2005	0	0	MTBS
Wildfire, human	2006	0	0	MTBS
Wildfire, human	2007	0	0	MTBS
Wildfire, human	2008	2	599	MTBS

occurrence has clear relations to extreme weather (Bessie and Johnson, 1995) and climate variables capturing drought and moisture availability and vegetation productivity in the preceding year (Swetnam and Betancourt, 1990; Westerling and others, 2006; Falk and others, 2007). Similarly, severe insect outbreaks often are related in part to climate conditions (Gan, 2004; Aukema and others, 2008). Broad-scale patterns of land use and land cover (LULC), topography, and population also may play significant roles in explaining disturbance patterns, especially for human-caused wildfire ignitions (Cardille and others, 2001; Syphard and others, 2007). By using previously identified relations, researchers will use statistical methods to test ecoregion-scale relations among recent disturbance occurrence, weather, climate, LULC trends, and population trends. General linear models will be used with negative binomial and Poisson responses for the number of disturbances and Gaussian responses for area affected; however, other statistical techniques may be used where appropriate. For certain disturbance types, such as hurricanes, where there is little evidence

of a long-term trend, relations with climate and other broad-scale predictors may not be identified. In such cases, the recent annual disturbance summaries will be used to simulate future disturbance occurrence patterns.

C.2.2. Fine-Scale Relations

Ecoregion-level relations will explain broad-scale patterns in terms of the number of disturbance events and total area disturbed each year; however, they provide minimal information about exactly where within ecoregions the individual disturbance events are most likely to occur. These patterns will be explained by using a second suite of empirical methods that predict the probability of disturbance at fine spatial resolutions (250-m pixels) and will incorporate fine-scale relations between disturbance-occurrence patterns and vegetation types, topography, and land use—especially from human pressures. For instance, abiotic and anthropogenic variables have been shown to be effective predictors of human-caused wildfire ignitions (Cardille and others, 2001; Syphard and others, 2008). Similarly, many of these same variables also have been shown to affect insects and disease because of preferential selection for certain hosts or vegetation types and transport by humans to previously unaffected areas (Prasad and others, 2010) in addition to topographic position, climate conditions, and previous outbreak locations (Dodds and others, 2006; Aukema and others, 2008; Santos and Whitham, 2010). In contrast, the likelihood of hurricane, tornado, and wind damage is largely dependent on vegetation type and topographic position (Boose and others, 2001; Kramer and others, 2001; Ramsey and others, 2001; Schulte and others, 2005). For each disturbance type, potential predictors will be identified from existing studies, and the relation between disturbance locations and predictors will be tested and quantified using statistical methods.

C.3. Future Ecosystem Disturbance

For the national assessment, projections of future disturbance events will be made for each of the reference and enhanced carbon-sequestration scenarios. The number of events and area affected by each disturbance will be projected using the previously identified ecoregion-scale and fine-scale methods (sections C.2.1 and C.2.2 above). To incorporate management activities, model parameters, probabilities, and predictions may be altered. For example, an increase in a prescribed fire-use scenario may simply double the number of prescribed fires simulated in any given year. Ecosystem disturbance modeling will be conducted and reported for EPA level II ecoregions. The details of the modeling steps for each disturbance type and incorporation of mitigation and management actions are provided in the following sections.

C.3.1. Wildfire (Human Caused and Natural)

Simulations for wildfires will be made for each EPA level III ecoregion for each reference and enhanced scenario

and reported by EPA level II ecoregion. Predictions of annual ecoregion fire activity (n wildfires per year) will be based on previously developed empirical relations with broad-scale climate and LULC variables (section C.2.1 above). Ignition locations of individual fire events will be based on an additional set of probability surfaces based on empirical relations with weather, climate, vegetation, topography, and LULC (section C.2.2 above). Once ignition locations are determined, individual fire spread will be simulated using the minimum-travel-time (MTT) algorithm (Finney, 2002), the LANDFIRE fuels and topography layers (Rollins, 2009), and the fire-weather climatology derived from the NOAA North American Regional Reanalysis (NARR) weather data. Following fire spread, emission estimates will be summarized for each fire using the Consume and FOFEM models and the FCCS and FLM data produced by LANDFIRE (Rollins, 2009).

C.3.2. Fuel Treatment (Including Prescribed Fire)

Simulations for fuel treatments will be run for EPA level III ecoregions for each reference and enhanced scenario. Predictions of annual ecoregion treatment activities will be based on a random selection from the recent probability distribution of fuel-treatment activity (n treatments and area treated per year), but may be modified in terms of the number of treatments per year or area treated per year under the different enhanced scenarios. Individual fuel treatments will be restricted to public lands and randomly placed within wildland vegetation types depending on the type of treatments; for instance, forest-fuel thinning cannot occur in grasslands. Nonfire treatments will expand using a patch-grow algorithm until a final predicted treatment size is reached, or an entire contiguous wildland vegetation patch is treated. For prescribed fire-fuel treatments, the MTT fire-spread algorithm used by the wildfire modeling will be used (section C.3.1 above). The LANDFIRE fuel data layers will be updated after placement of fuel treatments, to account for treatment effects on fire behavior and spread.

C.3.3. Insect and Disease Activity

Simulations will be run for EPA level III ecoregions for each reference and enhanced scenario. Predictions of annual ecoregion-level insect and disease activity (area affected per year) will be based on ecoregion empirical relations derived from epidemiological and species distribution modeling techniques (section C.2.1 above; Elith and others, 2006; Phillips and others, 2006; Elith and Leathwick, 2009) using climate, vegetation, topography, and previous outbreaks as predictors. Because of the potentially large number of unique insect species and diseases that could be simulated, spatially explicit species-occurrence modeling will be prioritized on the basis of the amount of area currently (2010) affected and the effect on standing biomass; example insects include the mountain pine beetle (*Dendroctonous ponderoseae*), the southern pine beetle

(*Dendroctonus frontalis*), and the gypsy moth (*Lymantria dispar*) (Krist and others, 2007). In cases where it is not possible to generate statistically and ecologically significant, spatially explicit probability surfaces, ecoregional probability distributions will be used instead.

C.3.4. Tornado and Damaging Wind Events

Tornado and damaging wind simulations also will be made for EPA level III ecoregions under each reference and enhanced scenario. Ecoregion-level predictions of tornado activity (*n* storms per year) will be based on a random selection from regional summaries of recent occurrences. Then for each simulated tornado, an empirical storm-track generator (Vickery and others, 2000) will establish the tornado path. The width of the tornado-disturbance footprint will be determined from the recent distribution of storm track widths measured using remote sensing of landscape change (section C.1.1 above). If wind damage to vegetation can be effectively monitored from remote sensing of landscape change, then damaging wind models will be made similarly to tornado methods. Historic frequencies of the number of damaging wind events and area affected will be used to simulate future occurrence patterns.

C.3.5. Hurricane Events

Hurricane effects often occur over areas larger than the EPA level III ecoregions used for other disturbance types; therefore, hurricane simulations will run annually, but for the entire United States for each reference and enhanced scenario. Predictions of hurricane activity (*n* storms per year) will be based on a random selection from regional summaries of recent occurrences. As with tornadoes, an empirical storm-track generator will create a storm path and wind speeds along the path for each hurricane (Vickery and others, 2000). A surface wind-field and exposure probability surface based on topography and vegetation, calibrated with remote sensing of landscape change data, will determine areas where vegetation damage will occur (Boose and others, 1994).

C.4. Disturbance Model Outputs

Disturbance model outputs are listed in table C1 and will include tabular annual summaries of the number of events and area affected for each disturbance type or management activity for each assessment unit. Additionally, tabular summaries of annual greenhouse-gas emissions (methane, carbon monoxide, carbon dioxide, and nonmethane hydrocarbons) will be produced for wild and prescribed fires. Disturbance maps with 250-m spatial resolution also will be generated annually, with unique labeling for specific disturbance types. These outputs will be provided for recent disturbances (1984–2010) and future disturbances (2011–2050). Models will be run using a Monte Carlo framework to quantify uncertainties, and as a result,

projection outputs will be presented as probability distributions representing the range of variability in potential outcomes.

C.5. Vegetation Dynamics

At the end of each year in the LULC-change model and disturbance-model simulations, updates will be made to vegetation-type and fuel data layers to incorporate the effects of disturbances, management actions, LULC, and vegetation succession. Initial vegetation conditions will be established from the existing vegetation-type and succession-class data layers in LANDFIRE (Rollins and Frame, 2006; Rollins, 2009). Each vegetation type has an existing vegetation-dynamics model that defines transitions among a number of succession classes. Transitions will be initiated using disturbance type, severity, and time since last disturbance. These succession trajectories are defined from historic disturbance regimes, and the vegetation dynamics are being updated to incorporate modern disturbance types; for instance, forest harvesting and invasive species. Furthermore, LANDFIRE fuel-model layers are defined using the vegetation types and succession classes, thereby allowing updates to account for vegetation changes (Keane and others, 2001; Rollins and Frame, 2006). Thus, future vegetation-type, succession-class, and fuel models will be updated using the existing vegetation type and succession class and the outputs from the simulated disturbances and LULC changes.

C.6. Scenarios and Management Options

Management activities affecting fuel and ignition patterns potentially can have effects on carbon storage and greenhouse-gas emissions. The disturbance task will allow different management activities in future scenarios that incorporate a range of fire-management strategies. Specifically, fuel treatments (including fuel reduction and prescribed fire) will allow for increases or decreases in the area of different fuel treatments to be specified under alternative scenarios. The disturbance model also will incorporate fire suppression and its effect on limiting the size of wildfires using a wildfire containment probability algorithm developed by Finney and others (2009). Finally, the disturbance model's probability surfaces are sensitive to LULC changes and, therefore, may demonstrate unintended effects of land-management policies on disturbance regimes.

Management activities and the extent to which they affect disturbances will be simulated for each of the IPPC reference and enhanced scenarios. See section 3.3.1 of this report for details of the scenario development. Specifically, information will be gathered using questions such as "Within the A2 storyline, would it be feasible to double the area treated using prescribed fire in your region?" The results will be compiled into a management portfolio for each scenario and will be used to assess how different mitigation strategies might affect biological carbon storage and greenhouse-gas emissions.

C.7. Relations to Existing Disturbance Models

The modeling approach for future potential fires parallels other fire-modeling efforts in the United States, but there are some important differences. Desktop applications such as Fire Area Simulator (FARSITE) and FlamMap (a USFS fire-behavior mapping and analysis model) are used to examine individual fire events or landscape-level fire behavior. FARSITE simulates individual fire growth given an ignition point (Finney, 2004) and is considered to be "state of the art" in terms of fire-spread simulation, but the computation requirements are expensive and that prohibits its use for national-scale assessments. The MTT algorithm, which is used for the national assessment, produces similar results with less of a computational burden (Finney, 2002). The MTT algorithm is integrated into FlamMap and relies on landscape-level fire behavior outputs produced by FlamMap to simulate fire growth in addition to other fire-behavior indices across a landscape (Finney, 2006). The Fire Spread Probability model (FSPro) simulates fire spread using the MTT algorithm from thousands of randomly placed fire ignitions and stacks the results to produce burn probabilities. FSPro is integral to the wildland fire decision-support system (WFDSS) and fire program analysis (FPA). This approach is similar to FSPro in many ways because the same fire-spread algorithm is used; however, instead of generating burn probabilities like FSPro, this method generates individual burn perimeters and interacts with the LULC change model and the biogeochemical cycling model.

C.8. Integrating Land-Use- and Land-Cover-Change Modeling and Biogeochemical Modeling

There are reciprocal feedbacks among the primary modeling components, with the disturbance model, LULC-change model (appendix B of this report), and biogeochemical model (appendix E of this report) sharing data before and after each year in the simulations. At the end of each annual disturbance-model simulation, the results will be communicated to the LULC-change model and the biogeochemical model. The biogeochemical and LULC-change models do not require the level of thematic and spatial detail provided by the LANDFIRE vegetation types; therefore, the LANDFIRE vegetation-type layer will be aggregated to 250-m pixels and reclassified to National Land Cover Database (NLCD) categories using a look-up table at the end of each year in the disturbance-model simulations. The updated layer will then be transferred to the LULC-change model, and eventually to the biogeochemical model for calculating carbon stocks and greenhouse-gas fluxes for the current model-simulation year. In turn, the LULC-change modeling component will provide an updated land-cover layer to the disturbance-model component so that disturbance probability surfaces can be updated to reflect any changes that occurred.

Additionally, the biogeochemical-model component will provide information on biomass-pool changes because of growth, mortality, and decomposition to recalibrate fuel-load data.

C.9. Ecosystem-Disturbance Data Needs

Representing the range of disturbances affecting ecosystem carbon stocks and greenhouse-gas fluxes depends largely on the availability of input data needed to parameterize and execute the various disturbance components. Fires and fuel treatments have the most complete existing datasets; however, even these datasets have limitations. Many fires are not mapped by the MTBS project, especially small fires and unreported fires occurring on public and private lands (Eidenshink and others, 2007). The NFPORS fuel-treatment database lacks the spatial detail and treatment-effects information needed for more sophisticated modeling. Other disturbance types, especially insect outbreaks and storms, lack data documenting the extent and effects of these disturbances with enough detail to use for the modeling efforts. Even though the capability to use remote-sensing data or aerial surveys to track storm and insect damage has been demonstrated, nationally consistent datasets currently (2010) are lacking. Consequently, these data gaps will limit the ability to account for the effects of all disturbances on ecosystem carbon storage and greenhouse-gas fluxes. Future research is needed to identify the most suitable algorithms and approach to generate a comprehensive land-disturbance and severity inventory for the Nation for use in carbon and greenhouse-gas assessments, and to develop models sensitive to climate and land change to project future disturbance-occurrence patterns.

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[Reports that are only available online may require a subscription for access.]

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Appendix D. Methods for Assessing Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes of Terrestrial Ecosystems

Quantifying terrestrial carbon dynamics for large regions is a challenging task for scientists (Potter and others, 1993; Intergovernmental Panel on Climate Change, 1997; Houghton and others, 1999; McGuire and others, 2002; Liu, Loveland, and Kurtz, 2004; Parton and others, 2005; Sierra and others, 2009). Generally, two approaches are used to quantify terrestrial carbon dynamics for large regions. The first of these is the spreadsheet or bookkeeping approach (Intergovernmental Panel on Climate Change, 1997; Houghton and others, 1999) that relies on a set of predefined carbon-response curves (for example, tree-growth curves) and uses regression equations or look-up tables; however, most carbon-response curves are created locally on the basis of limited categories of site conditions. They may be insufficient for capturing the effects of the spatial and temporal variability of land use, soils, and climate on carbon dynamics. The second approach depends on process-based biogeochemical models (Schimel and others, 1994; Melillo and others, 1995; McGuire and others, 2002; Chen and others, 2003; Potter and others, 2005; Tan and others, 2005; Liu and others, 2006). Instead of predefining the carbon-response curves under typical conditions, as in the bookkeeping approach, this process-based approach simulates carbon dynamics under specific and changing environmental and management conditions. Although it is capable of capturing detailed responses to changes in the driving variables, it usually requires more complicated input data and parameters.

Many site-scale process-based biogeochemical models were developed during the past 20 years (Parton and others, 1987; Running and Coughlan, 1988; Li and others, 1992). They benefitted from an improved understanding of biogeochemical processes resulting from controlled experiments and field observations. For regional studies, however, these models usually were directly applied to grid cells (for example, 0.5 × 0.5 degrees longitude and latitude) that were larger than the site scale (Melillo and others, 1995; Pan and others, 1998; McGuire and others, 2001; Potter and others, 2005) without incorporating information on field-scale heterogeneities. This can result in significant biases in the estimations of important biogeochemical and biophysical processes (Avissar, 1992; Pierce and Running, 1995; Turner and others, 2000; Reiners and others, 2002). Therefore, deploying field-scale ecosystem models to generate regional carbon-sequestration estimates with measures of uncertainty is a challenge.

The General Ensemble Modeling System (GEMS) was designed to facilitate the application of classic site-scale models on a regional scale and to better integrate well-established ecosystem biogeochemical models by using a Monte Carlo-based ensemble approach to incorporate the probable occurrence of parameter values in simulations. Consequently, GEMS not only drives biogeochemical models to simulate the spatial and temporal trends of carbon and nitrogen dynamics, but it also determines uncertainty estimates of the predicted variables. GEMS previously has been applied in this way to simulate carbon dynamics for large areas in Africa (Liu, Kaire, and others, 2004) and the United States (Liu, Loveland, and Kurtz, 2004; Tan and others, 2005; Liu and others, 2006).

The spreadsheet and biogeochemical modeling approaches that will be used to quantify biological carbon sequestration and greenhouse-gas (GHG) emissions for the national assessment are described in detail in the following sections. In addition, model uncertainty, model integration with other model systems, and ecosystem-services modeling are described.

D.1. Accounting and Modeling Simulations of Carbon Sequestration and Greenhouse-Gas Fluxes

D.1.1. GEMS Accounting Using the Spreadsheet Approach

Spreadsheet approaches use a computer spreadsheet tool to simulate carbon dynamics and GHG emissions. The primary advantages of the spreadsheet approach are ease in model development and model transparency. The disadvantages of the spreadsheet approach include nonspatial or coarse spatial resolution of simulations and the relatively small number of formulas used in spreadsheet calculations. Nevertheless, although many processes have to be simplified or ignored, the spreadsheet approach provides reference results that are useful to compare with those from more process-based modeling systems.

In general, carbon accounting for almost all terrestrial sectors can be conducted using the spreadsheet approach. The 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, 2006) provides equations and factors for building GHG spreadsheets. A spreadsheet approach will be implemented in parallel to GEMS to compare and verify GEMS outputs; this method is called "GEMS-spreadsheet."

The GEMS-spreadsheet method requires the following input data at the ecoregion level (or any geographic region):

- Land-cover transition tables during two periods (for example, 2001–2010 and 2011–2050)
- Vegetation-age distribution by land-cover type
- Carbon density by age and land-cover type
- GHG fluxes by vegetation age and land-cover type

- The severity of disturbances or management activities on live biomass carbon, expressed as the fraction of biomass killed or harvested

- Carbon transfer coefficients among different pools, including the atmospheric carbon dioxide (CO_2) pool

- Carbon decomposition rates in various pools

The GEMS-spreadsheet method tracks the carbon stock of unchanged land units (that is, no land-cover transitions) in carbon pool p_1 in a given region using the following accounting procedure:

$$C_{t,p_1} = \sum_i^n \sum_j^m A_{t,i} a_{t,i,j} c_{t,i,j,p_1} \,, \tag{D1}$$

where n and m are the number of land-cover classes and age classes, respectively,

$A_{t,i}$ is the total unchanged area of land-cover class i at time t,

$a_{t,i,j,}$ and c_{t,i,j,p_1} are, respectively, area fraction and carbon density of land-cover class i, at time t, and in age class j.

Carbon-density values will be derived from the U.S. Forest Service's (USFS) Forest Inventory and Analysis (FIA) program data. Land-cover transitions and age-distribution information will be from the "forecasting scenarios of land-cover change" (FORE–SCE) model.

For those land units that experienced land-cover transitions, the following procedures are used to track carbon flow among different pools:

$$C_{t,p_1 \to p_2} = \sum_{i=1}^n \sum_{j=1}^n A_{t,i,j} c_{t,i,p1} \alpha_{i,j,p_1 \to p_2} \,, \tag{D2}$$

where $A_{t,i,j}$ is the area changed from land-cover class i to j at time t;

c_{t,i,p_1} is the average carbon density in pool p_1, and

$\alpha_{i,j,p_1 \to p_2}$ is the fraction of carbon density in pool p_1 that is transferred to p_2 because of land-cover transition from i to j.

In the GEMS-spreadsheet method, carbon is transferred among the live and dead, aboveground and belowground biomass pools and the wood-products pool (harvested materials). Carbon-transfer coefficients will be developed based on expert knowledge, remotely sensed data (for example, fire severity), and output from disturbances modeling.

The decomposition of carbon in a given pool (except the live biomass pool) is calculated as follows:

$$C_{t,p \to CO_2} = -\beta_{p_1 \to CO_2} C_{t,p_1} \,, \tag{D3}$$

where $\beta_{p_1 \to CO_2}$ is the decomposition rate of carbon in pool p_1, defined as a fraction of the pool size.

In summary, the carbon stocks in live biomass, aboveground and belowground dead biomass, and wood products in a region at time t are calculated as follows:

$$C_{t,p_1} = C_{t,p_0} + \sum_{p_2=1}^k C_{t,p_2 \to p_1} + C_{t,p_1 \to CO_2} \,, \tag{D4}$$

where k is the number of carbon pools.

The total regional nitrous-oxide (N_2O) and methane (CH_4) fluxes are calculated as follows using the GEMS-spreadsheet method:

$$F_t = \sum_i^n \sum_j^m A_{t,i} a_{t,i,j} \lambda_{t,i,j} \,, \tag{D5}$$

where $\lambda_{t,i,j}$ is the flux of N_2O or CH_4 per area on land-cover class i, at time t, and in age class j.

Region-specific GHG fluxes for different ecosystems under various management practices will be compiled from extensive literature review and metadata analysis.

D.1.2. GEMS Biogeochemical Modeling

GEMS provides spatially explicit biogeochemical-model simulations for large areas. The overall GEMS input-data requirements and model functions are shown in figure D1,
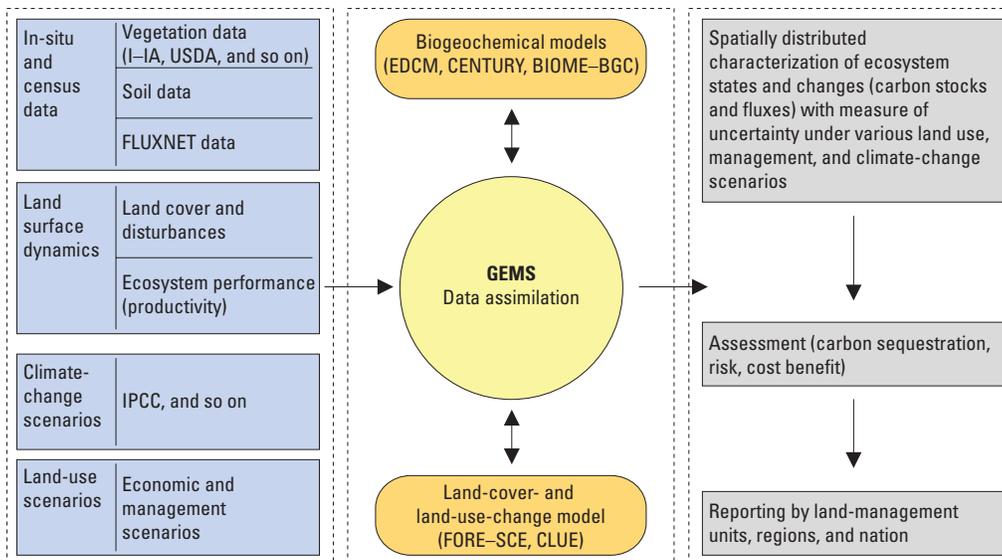
Figure D1. Diagram showing functionality and major types of input data for the General Ensemble Modeling System (GEMS). FIA, Forest Inventory and Analysis Program (U.S. Forest Service); USDA, U.S. Department of Agriculture; EDCM, Erosion-Deposition-Carbon Model; BIOME–BGC, biome biogeochemical cycles; IPCC, Intergovernmental Panel on Climate Change; FORE–SCE, "forecasting scenarios of land-cover change" model; CLUE, Conversion of Land Use and its Effects model.

which indicates that GEMS, as an expandable framework, can process various land-use and disturbance data and link with existing models and tools. GEMS uses two approaches to interact with encapsulated biogeochemical models: agent and direct implementation.

D.1.2.1. Ensemble Models or Agent Implementation

A special model interface (that is, the agent) controls diverse plot- and regional-scale models in GEMS. This approach requires minimum or no modifications to the underlying biogeochemical models and can be useful for reusing models that are difficult to modify. Under the "agent implementation" mode, GEMS uses plot-scale ecosystem biogeochemical models to simulate carbon and nitrogen dynamics at the plot scale. It controls these site-scale models by automatically parameterizing them according to the biophysical conditions of any land parcel and deploying them across space without considering the interactions among land pixels. Plot- and regional-scale biogeochemical models, such as the Century model (Parton and others, 1987), the Erosion-Deposition-Carbon Model (EDCM; Liu and others, 2003), and the Integrated Biosphere Simulator (IBIS; Foley and others, 1996), can serve as encapsulated ecosystem biogeochemical models in GEMS (Tan and others, 2005; Liu and others, 2006). Because GEMS is designed to encapsulate multiple models, and parameterize and execute these models using the same data, it provides an ideal platform to conduct "model ensemble" simulations to identify and address issues and uncertainty related to model structure and mathematical representations of biophysical processes.

To ensure a nationally consistent approach for selecting biogeochemical models for the assessment, a modeling workshop will be held in summer of 2010, and national ecosystem modeling experts will be invited to help identify additional suitable models. Model selection will address the ability to consider the effects of land-use and land-cover change, major disturbances, and climate change on carbon sequestration and GHG emissions. Predefined criteria are listed in table D1; this list does not mean that a single biogeochemical model must meet all these criteria.

D.1.2.2. Direct Implementation

Biogeochemical models, such as EDCM and Century, are merged directly with GEMS to allow more efficient, spatially explicit simulations. Many regional model applications adopt a time-space simulation paradigm, which runs a simulation for an individual pixel from beginning to end in time before moving to the next pixel. In the direct implementation (for example, GEMS–EDCM), the space-time sequence paradigm will be used instead (thus, GEMS simulates the whole region for a given time step first, then moves to the next time step). The space-time sequence paradigm provides easy ways to integrate with other modeling systems such as FORE–SCE ("forecasting scenarios of land-cover change" model), USPED (Unit Stream Power-Based Erosion Deposition), and the disturbance models in a parallel computation fashion; lateral movements of carbon and nitrogen can be effectively quantified as well.

Table D1. Tentative selection criteria and checklist for biogeochemical models to be included in the General Ensemble Modeling System (GEMS).

[CO_2, carbon dioxide]

Criteria	Questionnaire checklist
Ecosystem processes	Include ecosystem carbon, nitrogen, and water cycles?
	Include ecophysiological processes (for example, photosynthesis)?
	Consider major ecosystem disturbances (fire, logging)?
	Consider major ecosystem management activities?
Ecosystem types and carbon pools	Include all major natural forest/shrub/grassland systems?
	Include agricultural ecosystems?
	Include wetland ecosystems?
	Include major vegetation and soil carbon/nitrogen pools?
Model structure and reuse	Allow for parallel model simulation?
	Well modularized and easy to be incorporated into GEMS?
	Coded in familiar programming language (C/C^{++}, Fortran)?
Scientific rigor	Model is well accepted and published?
	The team has some experience with the model?
	Allow sensitivity testing on key driving variables (for example, climate, CO_2)?

Detailed descriptions of GEMS–EDCM, including its theoretical basis, general structure, simulation capability, and unique approach are provided in the following sections.

D.1.2.3. GEMS Data Flow and Linkages With Other Modeling Products

The overall GEMS flow chart of data and processes, including the spatial simulation unit setup, the Monte Carlo process, biogeochemical-model simulation, data assimilation, network Common Data Form (NetCDF) data processing and visualization, the post-simulation process, and uncertainty assessment are shown in figure D2. The model also is capable of parallel simulations to estimate lateral carbon-nitrogen movements. These processes and data are described in detail in the following sections.

D.2. GEMS Modeling

D.2.1. Major Processes Affecting Carbon Sequestration and Greenhouse-Gas Fluxes in GEMS

The overall processes of land-atmosphere interactions (for example, vertical fluxes of carbon and nitrogen), lateral fluxes of carbon and nutrients, and the pertinent controlling mechanisms in GEMS are shown in figure D3. The simplified carbon cycle, which is the main biogeochemical cycle modeled with GEMS, includes gross primary productivity (GPP), net primary productivity (NPP), photosynthesis allocations (to leaf, root, stem), litter fall, mortality, debris accumulation, and decomposition of soil carbon. The carbon cycle is tightly coupled with nitrogen and water cycles. The water cycle includes algorithms to estimate rain interception,

Land-cover trends

LANDFIRE VCT

LANDFIRE MTBS

FIA stand age and biomass

Soil texture, soil carbon, soil erodability factor

Crop species, yield, irrigation, fertilization

Upland erosion (USPED)

Monte Carlo downscaling

Disturbance effect look-up table (cutting, burn, and insect damage)

(Field observations) NASS, NAWQA, MODIS data, crop yield, FLUXNET

Spatial simulation units (JFD)

Initial site condition and disturbance effects

Biogeochemical models (EDCM, DNDC, IBIS, and so on)

Start—independent variable

NLCD land-cover data

Various climate data

DEM and hydrological data

STATSGO2 and SSURGO data

Ecoregion and administrative boundaries

Wetland data (NWI)

Atmospheric data (atmospheric CO_2 concentration, nitrogen deposition)

Other applicable data

JFD Builder and Monte Carlo downscaling

Use IPCC and FORE–SCE scenarios (NetCDF data)

FORE–SCE model

Historical? No Yes

LOOP–4   LOOP–3   LOOP–2   LOOP–1

Proceed to next year

Proceed to next JFD/pixel

Proceed to next run

EnKF data assimilation

Field data exist? Yes No

All ensemble runs finished? No Yes

All JFD/pixels finished? No Yes

All years finished? No Yes

River and coast model

Biomass carbon, litter and soil carbon, carbon fluxes, sediment, and so on

Final reporting items

Post-processing, uncertainty

Figure D2. Flow chart of the General Ensemble Modeling System (GEMS) for biogeochemical simulations. Abbreviations are found in "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report.

evaporation, transpiration, runoff, and soil water content. The water cycle is also linked with soil organic carbon decomposition and plant growth through soil water availability. The nitrogen cycle is coupled with the carbon cycle through nitrogen availability that controls plant growth and soil carbon decomposition. External driving forces are climate variation and change, human land-management activities, and natural disturbances. These forces and their effects are discussed in subsections below in this appendix. CH_4 and N_2O emissions will be quantified using available equations within biogeochemical models. If unavailable, other empirically derived approaches will be adopted (for example, the model of Cao and others (1996)).

D.2.1.1. Ecosystem Production

Quantification of ecosystem production starts with vegetation photosynthesis, which will be modeled using three different approaches in GEMS to overcome the disadvantages of any single algorithm. The three approaches include a light-use-efficiency approach (Yuan and others, 2007), a biochemical-modeling approach (IBIS; Foley and others, 1996), and a scalar approach (Century; Parton and others, 1993). For example, the algorithm for leaf photosynthesis in IBIS is a modified Farquhar-type model (Farquhar and others, 1980). The gross photosynthesis rate through light-limited, Rubisco-limited, and triosephosphate-utilization-limited mechanisms (Foley and others, 1996, equations 2, 4, and 5) is partly determined by intercellular CO_2 concentration within the leaf, which in turn determines the water conductance and CO_2 concentration at the leaf surface (Foley and others, 1996, equations 13, 14, and 15). The gross photosynthesis rate also is modified by the leaf nitrogen level, which is determined by the soil nitrogen pool (Liu and others, 2005, equations 1, 8, and 9). At the canopy level, IBIS allows the leaf area index (LAI) to change dynamically depending on living leaf biomass.
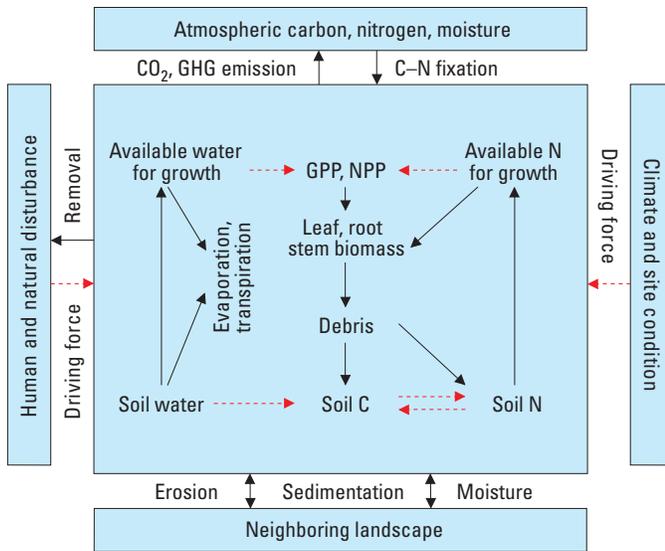
Figure D3. Diagram showing the interactions of the biogeochemical processes in the General Ensemble Modeling System (GEMS). Black arrows indicate mass flow and red arrows indicate control modifiers. CO_2, carbon dioxide; GHG, greenhouse gas; C, carbon; N, nitrogen; GPP, gross primary productivity; NPP, net primary productivity.

The diagram of the carbon-nitrogen flow in IBIS is shown in figure D4. Foliar nitrogen concentration is represented by the leaf carbon-to-nitrogen ratio (and is denoted as leaf_C:N), which is dynamically adjusted by a carbon-to-nitrogen modifier (K_{CN}), which is determined by soil mineral nitrogen content (N_M). The environmental conditions (radiation, water availability, temperature, and CO_2 concentration), the LAI, and the maximum Rubisco activity (V_m) as limited by available leaf nitrogen determine the canopy-level gross primary productivity (GPP_c). After deducting maintenance respiration (using the factor Maint_resp), GPP_c gives canopy-level NPP (NPP_c). At this point, NPP_c represents the production of pure carbohydrate, rather than of new biomass carbon. A fraction of NPP_c is consumed in growth respiration, with the remainder being converted to "stabilized" biomass (NPP_b). The remaining biogeochemical processes, especially soil decomposition, are similar to those of the Century model.

D.2.1.2. Soil Organic Carbon Cycle

EDCM is an embedded ecosystem biogeochemical model in GEMS. It is based on the well-established ecosystem model Century (version IV) (Parton and others, 1993; Liu and others, 2003). Both models use empirical maximum potential vegetation productivity, together with limitations from temperature, water, and nutrients, to calculate production of trees and crops. The established algorithms of soil organic carbon (SOC) dynamics in Century form the basis of several other biogeochemical models, such as the Carnegie-Ames-Stanford Approach (CASA; Potter and others, 1993), the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen and others, 2000), TRIPLEX (Peng and others, 2002),
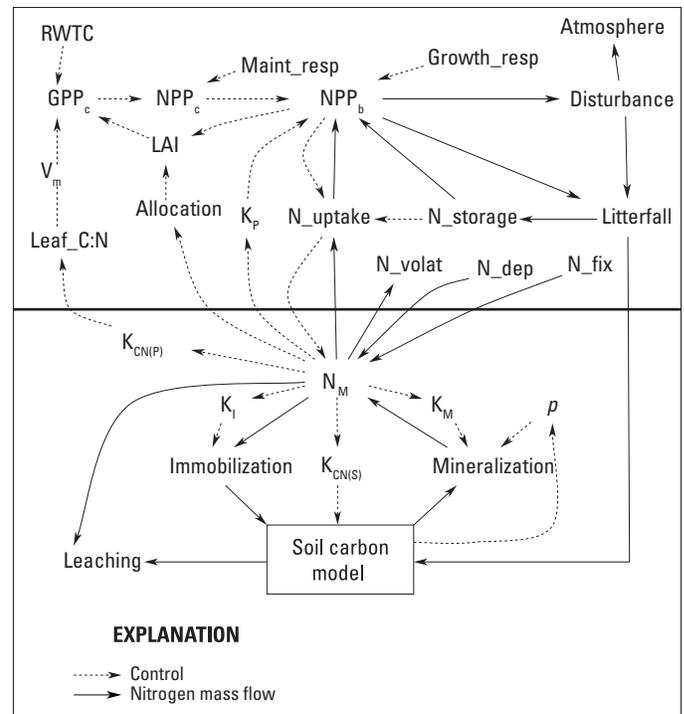

Figure D4. Diagram showing carbon-nitrogen cycles and nitrogen controls in the Integrated Biosphere Simulator (IBIS). Abbreviations and variables are as follows: GPP_c, Canopy-level gross primary productivity; Growth_resp, growth respiration ratio; K_P, Modifier of plant biomass construction; K_M, Modifier of soil organic matter (SOM) mineralization; K_I, Modifier of soil nitrogen immobilization; $K_{CN(P)}$, Modifier of plant (leaf) carbon-to-nitrogen ratio; $K_{CN(S)}$, Modifier of SOM carbon-to-nitrogen ratio; LAI, leaf area index; Leaf_C:N, leaf carbon-to-nitrogen ratio; Maint_resp, maintenance respiration N_dep, nitrogen deposition; N_fix, nitrogen fixation; N_storage, nitrogen storage; N_uptake, nitrogen uptake; N_volat, nitrogen volatilization; N_M, soil mineral nitrogen; NPP_b, Net primary productivity as new biomass; NPP_c, Canopy-level net primary productivity (pure carbohydrate); p, stimulation factor of SOM decomposition because of the priming effect; RWTC, Radiation, water, temperature, and carbon dioxide; V_m, Maximum Rubisco-limited carboxylation rate adjusted by leaf carbon-to-nitrogen ratio. Modified from Liu and others (2005), used with permission.

and IBIS (Foley and others, 1996). The soil nitrogen pools and fluxes in an agricultural system as simulated by Century and EDCM are shown in figure D5. All the nitrogen pools are tightly coupled with the carbon cycle.

Owing to its inheritance from its antecedent model (Century), EDCM is an advanced biogeochemical model that simulates the effects of various natural processes (for example, fires, hurricanes, atmospheric nitrogen deposition, atmospheric CO_2 "fertilization," climate change and variability, and erosion and deposition) and management practices (for example, grain harvesting, timber harvesting, fertilization, land-cover and land-use change, cultivation, fertilization, manure addition) on carbon and nitrogen cycles at the ecosystem scale. EDCM can simulate the effect of soil erosion and deposition on carbon
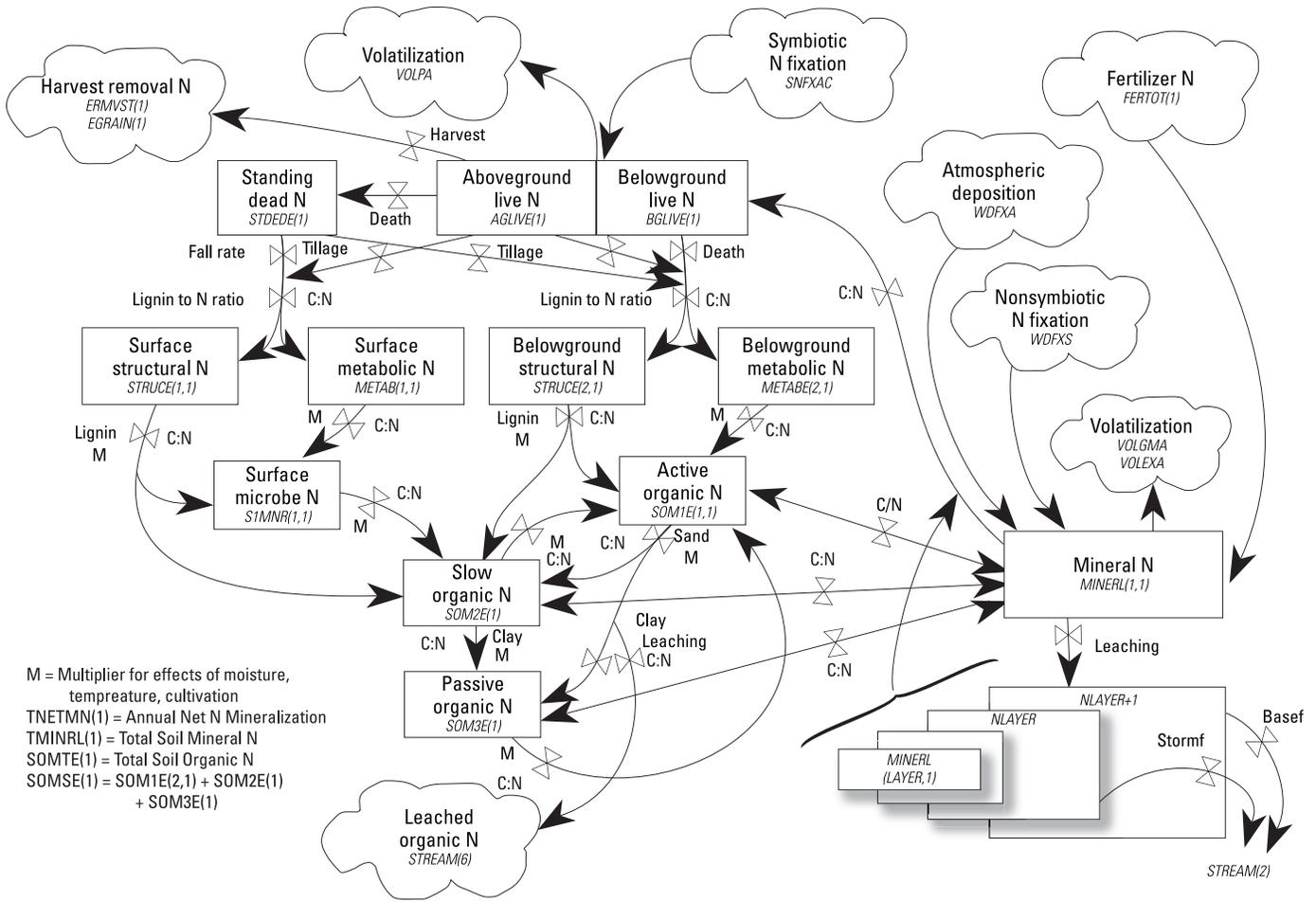
Figure D5.   Diagram showing nitrogen cycling in a terrestrial ecosystem as simulated by the Century model and the Erosion-Deposition-Carbon Model (EDCM). Modified from Metherell and others (1993), used with permission. The nitrogen cycle is tightly coupled with the carbon cycle. C:N, carbon-to-nitrogen ratio; N, nitrogen. Abbreviations are found in "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report.

and nitrogen dynamics. More than 100 output variables are provided by EDCM, including NPP, net ecosystem productivity (NEP), carbon and nitrogen stocks in aboveground and belowground biomass, soil carbon dynamics, and so on. Century has a one-soil-layer structure for carbon and nutrients (nitrogen, phosphorus, and sulfur). In contrast, EDCM adopts a multiple-soil-layer structure to account for the stratification of the soil profile and SOC in each soil layer. It dynamically tracks the evolution of the soil profile (up to 10 soil layers) and carbon storage as affected by soil erosion and deposition.

D.2.1.3. Effects of Disturbances

Natural and anthropogenic disturbances (for example, fires, hurricanes, tornadoes, and forest cutting) are accounted for in the land-use- and land-cover-change (LULCC) model. Ecosystem disturbances will be parameterized in the model separately because the biogeochemical consequences of these types of disturbances can be vastly different; however, the basic procedures are similar.

Historical fire perimeters and burn-severity maps are used in GEMS to indicate the timing, location, and severity level of burns. The extent and severity of a disturbance event are usually captured by remote sensing or field monitoring and also can be estimated by models, such as the First Order Fire Effects Model (FOFEM) by Reinhardt and others (1997) and the Landscape Successional (LANDSUM) model by Keane and others (2006). The effects of burns are expressed as biomass consumption loss and mortality loss (table D2). Based on the loss rates, GEMS reallocates biomass and soil carbon pools for each individual land pixel. Consumption loss is a direct carbon emission to the atmosphere, whereas motility loss converts live biomass carbon to dead carbon pools. The disturbed ecosystem will start regrowth with a new soil nutrient pool and a new LAI calculated in the model. Calculation of other disturbance effects will follow a similar approach to that used for fire effects, but with different carbon transition coefficients among various pools. The regrowth processes following disturbances are calculated based on light and water availability, temperature, nutrient availability, and

Table D2.   Fuel-consumption effects under different burn-severity levels, based on comparison of remotely sensed burn-severity and field observations.

[This table also is used in the fire-disturbance modeling tasks to calibrate fire-emission estimates. Source: Carl Key, U.S. Geological Survey, written commun., May 28, 2009]

Components	Consumption (percent)			Mortality (percent)		
	Low	Moderate	High	Low	Moderate	High
Forest floor and soil						
Litter/fine fuel	15–60	61–90	91–100	–	–	–
Duff	5–30	31–70	71–100	–	–	–
Medium fuel	10–30	31–50	51–100	–	–	–
Heavy	5–15	16–40	41–100	–	–	–
Soil	5–20	21–50	51–100	–	–	–
Understory layer						
Herb	16–60	61–85	86–100	–	–	–
Shrub-leaf-wood	10–40	41–80	81–100	–	–	–
Shrub-leaf-wood	–	–	–	1–20	21–70	71–100
Premature trees						
Leaf	1–20	21–70	71–100	–	–	–
Fine branch	1–20	21–70	71–100	–	–	–
Wood	–	–	–	1–20	21–75	76–100
Mature trees						
Leaf	1–20	21–70	71–100	–	–	–
Branch	1–20	21–70	71–100	–	–	–
Wood	–	–	–	1–20	21–70	71–100

other factors. GEMS assumes tree planting will follow the clearcutting event if a plantation is prescribed in the land-cover map, otherwise natural vegetation recovery will occur.

For the national assessment, simulated future-fire-disturbance maps will be produced along with (or embedded in) the future land-use and land-cover (LULC) maps. These disturbance maps (including simulated severity levels) will be linked with GEMS the same way as the LULCC maps are linked. Annual fluxes of disturbance-induced carbon loss and the legacy multiyear cumulative effects will be reported.

D.2.1.4. Effects of Management Activities

In addition to natural disturbances (for example, climate variation, geological disasters, wildfires), human management activities also play a critical role in annual ecosystem carbon fluxes and soil carbon budgets. For example, implementing conservation residue management can significantly mitigate carbon emissions from soils in comparison to conventional tillage management. The conceptual carbon-change scenarios based on explicit simulations of management effects and feedback are shown in figure D6.

Management activities considered in the current GEMS include (but are not limited to) the following:

- Land-use changes, including conversions between land-use classes and crop rotation
- Land-management practices, consisting of —
 - Logging event
  - Forest fertilization
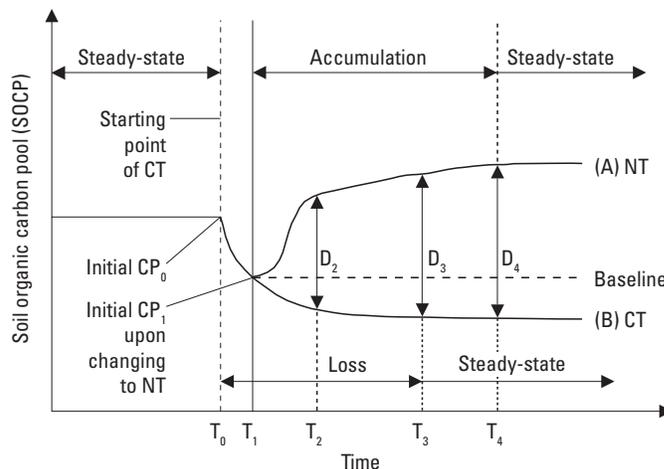
Figure D6.   Conceptual model of soil organic carbon (SOC) dynamics under a paired treatment of conventional tillage (CT) and no-till (NT) after initialization of cultivation from natural status. *A,* SOC gain upon converting from CT to NT following CT for a period of time (T_1–T_0). *B,* SOC loss caused by general cultivation practices associated with CT since T_0. Difference (D) in SOC stock between NT and CT varies with time. SOC reaches a new equilibrium at T_3 under CT and T_4 under NT. The rates of SOC gain and SOC loss do not coincide but are a function of the initial SOC stock level and time scale.

- Fire-fuel management, including prescribed burns
- Grazing (specified into various intensity classes)
- Tillage practices coupled with residue input
- Fertilization rate and manure application
- Irrigation

Key algorithms, such as irrigation, fertilization, and residue return, are embedded in GEMS. Data and parameter sets will be collected and compiled from existing databases and literature.

D.2.1.5. Effects of Erosion and Deposition

Soil erosion and deposition affect soil profile evolution, spatial redistribution of carbon and nutrients, and ecosystem carbon-nitrogen dynamics (Liu and others, 2003; Lal and others, 2004). Soil erosion and deposition will be simulated by using the USPED model (Mitas and Mitasova, 1998). The effects of soil erosion and deposition on soil carbon erosion will be quantified; the processes to be modeled include soil-profile evolution, onsite ecosystem-carbon dynamics, and offsite transport of carbon and nitrogen onto the landscape and into wetland environments and aquatic systems.

USPED is a simple two-dimensional hydrological model that is comparable to the more broadly used Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE); however, unlike the USLE/RUSLE models that can predict only soil erosion, USPED also can simulate deposition on landscape and requires only four major inputs:

- Rainfall intensity, which is to be adjusted by the actual rainfall each year

- Soil erodibility factor (K factor), which is available in the U.S. General Soil Map (also called the State Soil Geographic (STATSGO2) database) and the Soil Survey Geographic (SSURGO) databases

- Field carbon factor, which is directly converted from land-cover type

- Digital elevation model (DEM) data

Most of the input requirements are the same as those of USLE/RUSLE.

USPED is suitable for GEMS because of its appropriate time step, level of complexity, capability of simulating erosion and deposition, and robustness. For linking soil carbon with erosion and deposition, EDCM adopts a multiple-soil-layer structure to account for the stratification of the soil profile and SOC in each soil layer. EDCM dynamically keeps track of the evolution of the soil profile (up to 10 soil layers) and carbon storage as affected by soil erosion and deposition.

In EDCM, each soil-carbon pool in the top layer will lose a certain amount of carbon, if erosion happens. The carbon eroded is calculated as the product of the fraction of the top soil layer experiencing erosion, the total amount of SOC in the top 20 centimeters of the layer, and an enrichment factor for the eroded SOC to account for the uneven vertical distribution of SOC in the top layer. EDCM can dynamically update the soil layers affected by erosion and deposition.

One approach for linking USPED with GEMS is shown in figure D7. Simulated erosion and deposition are grouped into discrete classes, which will be included in the GEMS spatial simulation unit (joint frequency distribution (JFD) cases; see later explanations), to represent the land and water surfaces of the study area. Losses of carbon and nitrogen during lateral sediment transportation are accounted for using an oxidation factor.
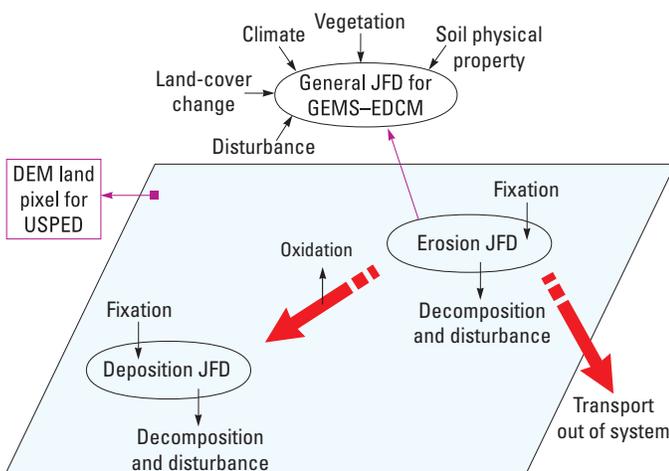

Figure D7.   Diagram linking the erosion-deposition model (USPED; Unit Stream Power-Based Erosion Deposition) with the terrestrial biogeochemical model (EDCM; Erosion-Deposition-Carbon Model) in GEMS (General Ensemble Modeling System). A JFD (joint frequency distribution) case indicates one or more pixels with the same site condition. DEM, digital elevation model.

D.2.1.6. Fate of Wood Products

Carbon in wood products, landfills, and other offsite storage can be significant in the accounting of terrestrial carbon-sequestration capacity (Skog and Nicholson, 1998). Currently (2010), GEMS does not track the fate of carbon in wood products. Because GEMS is linked directly to the data-management system for the purposes of reporting and dissemination of assessment results, a spreadsheet summarizing sequestration and GHG fluxes across ecosystems and carbon pools will be created. Most of the carbon pools will be simulated at a pixel level. For wood products, average values will be provided. The U.S. Environmental Protection Agency (EPA) and the USFS will be consulted about the proper way to estimate forest-product carbon and potential collaboration opportunities. Existing factors and equations about harvested-wood-product carbon pools (Smith and others, 2006; Skog, 2008) will be adopted and modified to link with GEMS to track the fate of harvested wood.

D.2.1.7. Methane and Nitrous-Oxide Fluxes

The emission of CH_4 at wetland sites will be simulated in terms of soil biogeochemical processes, including CH_4 production by methanogenic bacteria under anaerobic conditions, oxidation by methanotrophic bacteria under aerobic conditions, and transport to the atmosphere (Conrad, 1989). The principal controls of these processes are soil moisture, water-table position, soil temperature, availability and quality of suitable substrates, and pathways of CH_4 transport to the atmosphere. A wide range of models have been developed to simulate the plot-scale processes of CH_4 generation, consumption, and transport (Li and others, 1992; Cao and others, 1996; Potter, 1997; Walter and others, 2001; Zhuang and others, 2006). A simple compartmental (zero-dimensional) model was developed by Cao and others (1996) to simulate wetland carbon dynamics for large areas. Another model by Potter (1997) simulated CH_4 production rates from a microbial production ratio of CO_2 and CH_4, which changed as a function of the water-table depth. Slightly more complex one-dimensional models (Walter and others, 2001; Zhuang and others, 2006) also are available to tailor more detailed process descriptions. Some of these models have a detailed representation of plot-scale vertical soil processes. The deployment of these models for large areas, however, has been challenging because of the difficulties in defining parameters for these models and in simulating some of the critical driving variables, such as water-table position in individual wetlands for large areas.

The GEMS modeling team has applied the denitrification-decomposition (DNDC) model to simulate CH_4 and N_2O fluxes in the Prairie Pothole Region. A process-based model for CH_4 that is similar to the model in Cao and others (1996) and to DNDC approaches has been implemented in GEMS that will balance the needs of considering the plot-scale processes and the feasibility of deploying the plot-scale model for large areas to address spatial heterogeneity. Estimates of CH_4 production by the model depend on the substrate availability

(soil carbon and vegetation root carbon) and soil condition (soil temperature, redox), whereas CH_4 oxidation is calculated based on the soil redox condition or water table.

In a zero-dimensional modeling approach, the CH_4 emission from wetlands to the atmosphere is calculated as the difference between the CH_4 production and oxidation:

$$MER_t = MPR_t - MOR_t, \qquad (D6)$$

where MER_t is the emission mass of CH_4 per unit surface area of a wetland at time t,

MPR_t is the production mass of CH_4 per unit surface area of a wetland at time t, and

MOR_t is the oxidation mass of CH_4 per unit surface area of a wetland at time t.

MPR_t and MOR_t are estimated on the basis of such controlling factors as decomposed organic carbon, water-table position, soil temperature, and primary production of existing plants. These controlling factors are parameterized by applying or synthesizing techniques described in Cao and others (1996), Potter (1997), Walter and others (2001), and Zhuang and others (2006). A reasonably accurate prediction of the water-table position, in particular, is a challenging aspect. Further details are given below in section D.3.2 as part of a discussion on modeling lateral fluxes in and out of wetland systems.

Various models exist for simulating N_2O emissions (for example, Li and others, 1992; Liu and others, 1999; Parton and others, 2001; Hénault and others, 2005). Procedures for estimating N_2O emissions from ecosystems were developed in the prototype of the GEMS–EDCM method and applied to simulate and project N_2O emissions in the Atlantic zone of Costa Rica (Liu and others, 1999; Reiners and others, 2002). Nitrification and denitrification processes are the primary processes that lead to the emission of N_2O from soils. Atmospheric and terrestrial (for example, fertilizer, litter) depositions of nitrogen, plant uptake, mineralization, and leaching can act as the major controls. The existing GEMS algorithms for N_2O flux simulations will be used to compare simulation results with observations (for example, GRACEnet) and to improve the model when necessary. A zero-dimensional model is also applicable for estimating N_2O emissions from wetlands:

$$NOE_t = NOE_{denit,t} + NOE_{nit,t}, \qquad (D7)$$

where NOE_t is the N_2O emission mass per unit surface area of a wetland at time t,

$NOE_{denit,t}$ is the production mass by denitrification per unit surface area of a wetland at time t, and

$NOE_{nit,t}$ is the production mass by nitrification per unit surface area of a wetland at time t.

$NOE_{denit,t}$ and $NOE_{nit,t}$ are quantified by applying or synthesizing techniques described in Li and others (1992), Liu and others (1999), Parton and others (2001), and Hénault and others (2005).

Subject to the availability of observation data, empirical regression models also can be developed for emissions of CO_2,

CH_4, and N_2O from wetlands with different land-cover types, as well as hydrologic and meteorological regimes. Much of the variation in CO_2 and CH_4 may be explained by considering wetland soil temperature and water-table elevation as predictor variables. Variations of N_2O flux also could be captured by regressing with soil temperature and water-filled pore space as the predictor variables; however, such regression models probably are highly site-specific and require large datasets given their purely statistical nature. Because such datasets rarely exist in current literature, deployment of such models in large spatial (as well as temporal) scales can hardly be justified as reliable given the uncertainty of estimated regression coefficients.

The IPCC tier 1 approach (Intergovernmental Panel on Climate Change, 2006) is a simple way of obtaining crude estimations of CO_2, CH_4, and N_2O emissions from wetlands. The approach is based on some aggregate measures of emissions of specific GHG per unit of time and wetland area. Although IPCC (2006) provided global estimates of these emission factors based on existing literature, regional estimates for the wetlands in the United States also may be obtained from a comprehensive literature survey. Emission estimates obtained through the tier 1 approach would complement the evaluations of results of the simple biogeochemical models described previously.

D.2.2. GEMS Spatial Simulation Unit

The spatial heterogeneities of the biophysical variables (such as land cover, soil texture, and DEM) often are represented on thematic maps and stored in georeferenced geographic information system (GIS) databases. The simulation unit in GEMS is a cluster of land pixels sharing a unique combination of values of environmental driving variables. Combining multiple input raster layers (maps) on a cell-by-cell basis in a GIS, a JFD table can be created to list all unique combinations of the values of the overlay variables and their associated frequencies (areas or number of pixels). Each unique combination forms a GEMS simulation unit. The geographic locations of all the JFD cases are uniquely determined by the JFD map, thereby providing the spatial framework to visualize and analyze the spatial and temporal patterns of biogeochemical properties and processes.

Two examples of the JFD map are shown in figure D8. The first example (fig. D8A) shows the land pixel sampling at certain spatial intervals (for example, 5 kilometers) on a stack of relatively higher resolution (for example, 30- to 250-m) maps. This sampling approach is used when there are too many land pixels and map layers. It also creates a JFD table where each JFD case contains only one land pixel. The second example (fig. D8B) overlays the soil and land-cover maps; the resulting JFD map shows the unique combinations of soil and land-cover conditions. An important feature of this JFD approach is the elimination of the need to perform model simulations pixel by pixel. One pixel represents all the pixels of a JFD case.

A

B

EXPLANATION

Soil identification numbers

■	1
■	2
■	3
■	4
■	5
■	6

EXPLANATION

Land cover

■	Water
■	Agriculture
■	Mechanical disturbance
■	Developed
■	Forest
■	Wetlands
■	Grasslands/shrublands
■	Barren

EXPLANATION

Joint frequency distribution identification numbers

477

1
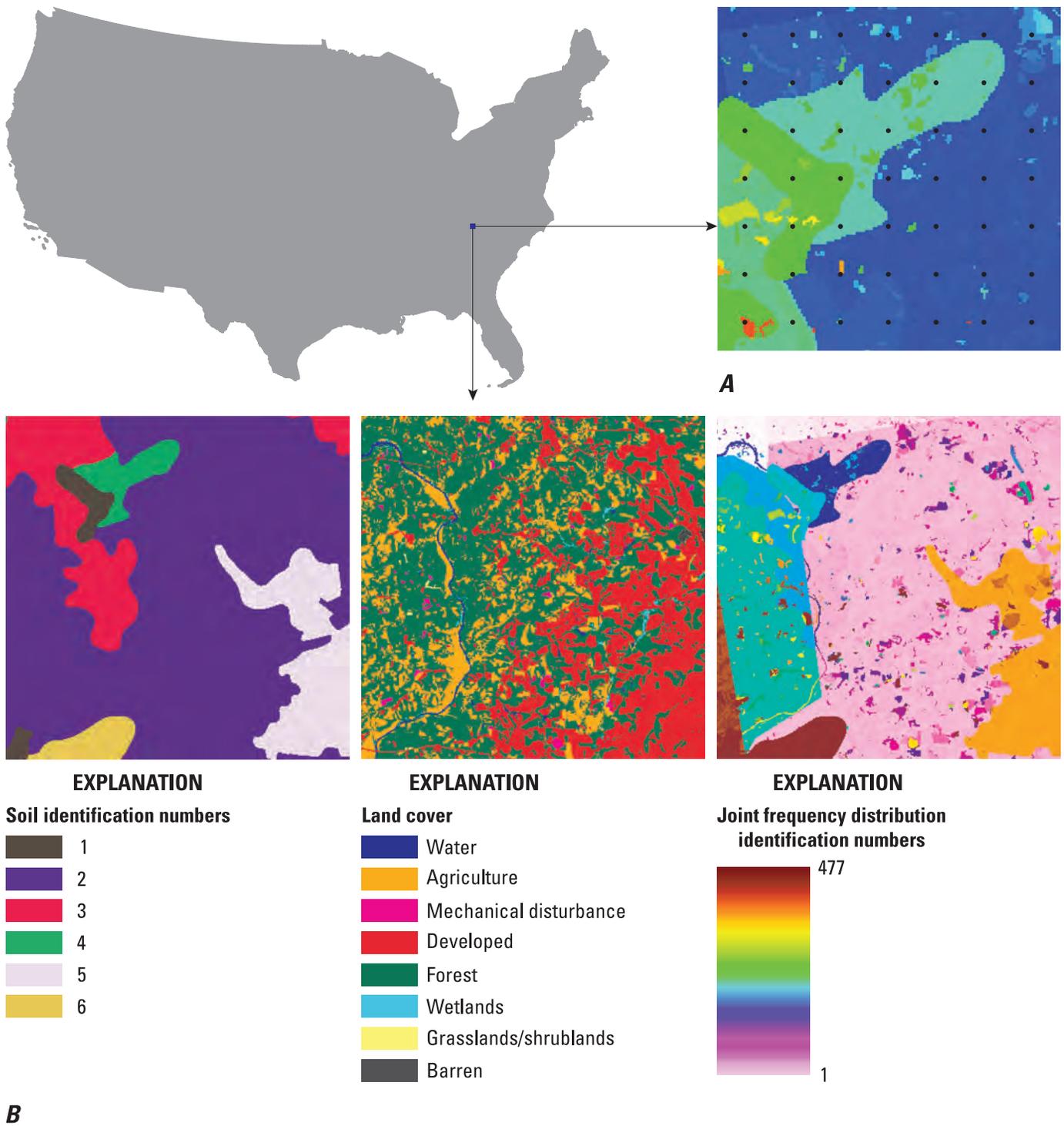
Figure D8. Conceptualized diagram showing two approaches to producing a joint-frequency distribution map. *A*, Sampling at certain spatial intervals. *B*, Overlaying the soil map with the land-cover map series produces the joint-frequency-distribution map; each image is 10 kilometers wide. (Note that the scales of parts *A* and *B* are exaggerated relative to the location map.)

D.2.3. Using Ensemble Simulations to Reconcile Nonlinearity and Heterogeneity

Studies indicate that averaging across the spatial and temporal heterogeneity of the input data could have significant effects on the carbon simulations (Avissar, 1992; Pierce and Running, 1995; Turner and others, 1996; Kimball and others, 1999). This indicates that incorporating ecosystem heterogeneity is necessary to accurately upscale carbon dynamics from site to regional scales. The direct approach of incorporating variance and covariance of input variables in the simulation process can be expressed as the following:

$$E(p) = \sum_{i=1}^{n} E[p(X_i)]F(X_i),\qquad \text{(D8)}$$

where E is the operator of expectation,
   p is the nonlinear model,
   X is a vector of model variables,
   n is the number of strata or total JFD, and
   F is the frequency of cells or the total area of strata i as defined by the vector of X_i.

Any difference between the model scale and the spatial resolution of the data may introduce biases caused by model nonlinearity. An ensemble approach can assimilate the fine-scale heterogeneities in the databases to reduce potential biases. The mean value of a variable (for example, carbon stock and flux) of simulation unit i in equation D8 can be estimated by using multiple stochastic model simulations:

$$E[p(X_i)] = \frac{1}{m}\sum_{j=1}^{m} p(X_{ij}),\qquad \text{(D9)}$$

where m is the number of stochastic fine-scale model runs for simulation unit i, and
   X_{ij} is the vector of model input values at the fine scale generated using a Monte Carlo
     approach within the space defined by X_i.

As a result, input values for each stochastic model run are sampled from their corresponding potential value domains (X_i) that usually are described by their statistical information, such as moments and distribution types. The variance of the model simulations on regional scale can be quantified as follows:

$$\sigma^2[p] = \sum_{i=1}^{n}\sigma^2[p(X_i)]F^2(X_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} Cov[p(X_i), p(X_j)]F(X_i)F(X_j),\qquad \text{(D10)}$$

where the variance and covariance of the model simulations on unit i can be expressed as follows:

$$\sigma^2[p(X_i)] = \frac{1}{m-1}\sum_{j=1}^{m}[p(X_{ij}) - E[p(X_i)]]^2 \text{ and }\qquad \text{(D11)}$$

$$Cov[p(X_i), p(X_j)] = E[p(X_i)p(X_j)] - E[p(X_i)]E[p(X_j)].\qquad \text{(D12)}$$

Other descriptive statistics, such as skewness, also can be calculated from the ensemble simulations. These moments characterize not only the spatial and temporal trends and patterns of simulated variables, but also their uncertainties in space and time.

Solving equation D10 will require excessive computational effort if the number of strata n is quite large; however, if $p(X_i)$ and $p(X_j)$ are independent among a great number of strata, computations will be dramatically reduced because covariance defined in equation D12 will be zero. Hence, actual applications should sufficiently identify the independence among strata. For example, suppose $p(X_i)$ and $p(X_j)$ represent soil organic carbon within strata i and strata j, respectively, and their random properties result from the randomness of soil texture and precipitation. If there is no lateral flow between strata i and strata j, then $p(X_i)$ and $p(X_j)$ can be regarded as independent.

D.2.4. Automated Model Parameterization (Monte Carlo Downscaling)

Models developed for site-scale applications need linkages with georeferenced data to be deployed across a region. Most information in spatial databases is aggregated to the map-unit

level as the mean or median values, making the direct injection of georeferenced data into the modeling processes problematic and potentially biased (Pierce and Running, 1995; Kimball and others, 1999; Reiners and others, 2002). Consequently, an automated model parameterization process usually is needed to incorporate field-scale spatial heterogeneities of state and driving variables into simulations. A Monte Carlo approach is built into GEMS to downscale aggregated information from map-unit level to field scale. Examples of data variables to be downscaled for parameterization include soil property, tree age, crop rotation, and forest cutting. The following describes the automated stochastic soil and forest-age initializations.

Soil polygons on the STATSGO2 and SSURGO maps are represented by map units; each has a unique map-unit identifier (ID), size, and location. Each map unit contains from 1 to 20 soil components, representing distinct soils types. Each soil component has a soil attributes table; however, the locations of the soil components within a map unit are not known. In GEMS, for any specific stochastic simulation, a soil component was randomly picked from all components within a soil map unit according to the probability defined by the areal fractions of the components. Once the component was determined, soil characteristics were retrieved from the corresponding soil component and layer attribute databases. For the variables with increased (V_{high}) and decreased (V_{low}) values, the following equation was used to assign a value (V) to minimize potential biases from model nonlinearity (Pierce and Running, 1995; Reiners and others, 2002):

$$V = \frac{V_{low} + V_{high}}{2} + \frac{p \times (V_{high} - V_{low})}{3.92}$$ (D13)

where p is a random value that follows standard normal distribution $N(0,1)$.

The above equation assumes that the possible values of the soil characteristics follow a normal distribution with 95 percent of the values varying between V_{high} and V_{low}.

The Monte Carlo approach also is used to downscale regional initial forest age. The currently available forest-age data come from State- or county-level forest-inventory statistics. The forest-age class distribution (area weight) is a feature on the regional scale. To assign a forest age for a specific location, a cumulative probability curve must be created on the basis of the forest-age class distribution (fig. D9). The next step is to generate a random p value between 0 and 1. The p value will point to a specific level on the cumulative probability curve and match it to a corresponding age class. GEMS then uses a look-up table to retrieve initial forest biomass based on the age (Liu, Liu, and others, 2008).

D.2.5. Data Assimilation

Data assimilation techniques can be activated to constrain GEMS simulations with various observations at different spatial and temporal scales. Different data-assimilation techniques are implemented in GEMS to leverage the advantages and disadvantages of each method. For example, the Markov Chain Monte
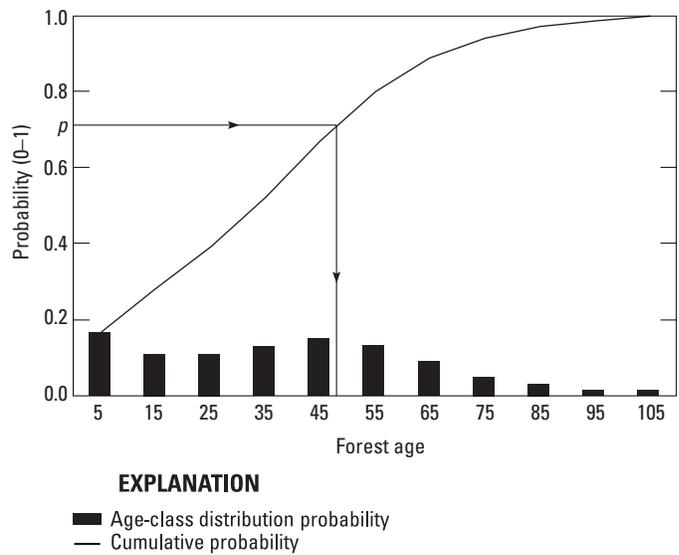
Figure D9. Monte Carlo downscaling of State- and county-level forest-age data to pixel level. From Liu, Liu, and others (2008), used with permission.

Carlo (MCMC) method is computation intensive and, therefore, difficult to apply to a region where the number of simulation units is large. It can be effective and ideal, however, to derive representative values and their uncertainties of model parameters from limited point observations, such as flux-tower measurements.

Other data assimilation techniques used by GEMS include model inversion using PEST (EPA's model-independent parameter estimation application; http://www.epa.gov/ceampubl/tools/pest/) (Liu, Anderson, and others, 2008), Ensemble Kalman Filter (EnKF) (Evensen, 1994, 2003), and Smoothed Ensemble Kalman Filter (SEnKF) (Chen and others, 2006, 2008). Model inversion with the PEST package is based on optimal theory and thus requires that the model have a smooth response to model parameters. Both EnKF and SEnKF are based on statistical Bayesian theory and joint technology of Monte Carlo sampling with a Kalman filter. EnKF has many successful applications in weather forecasting and hydrology through incorporating various data into the model simulation process to improve estimation of model state variables. The GEMS team has used some of the approaches to derive model parameter information from plot measurements of carbon and nitrogen stocks (Liu, Anderson, and others, 2008) and from eddy-covariance flux-tower observations (Chen and others, 2008). A combination of data-assimilation techniques will be used to ensure that model simulations agree well with observations from different sources and scales.

Plot-scale.—FLUXNET (the flux network) and FIA data (plot-scale repetitive measurements of biomass stocks and vegetation dynamics) will be used to derive information on model-parameter values and their uncertainty. The derived model-parameter information at the plot scale will then be extrapolated to regional and national scales (Liu and others, 2008).

Regional to national scales.—EnKF, SEnKF, or other data-assimilation techniques will be used to assimilate remotely

sensed and ground-based observations. For example, Zhao and others (2010) successfully assimilated the gross primary productivity (GPP) data of the Moderate Resolution Imaging Spectroradiometer (MODIS) products to support regional model simulations of carbon sequestration in a southeastern region.

The SEnKF (Chen and others, 2006, 2008) will be used at the plot and regional scales. By combining EnKF with a kernel smoothing technique, SEnKF has the following characteristics:

- Simultaneously estimates the model states and parameters through concatenating unknown parameters and state variables into a joint state vector

- Mitigates dramatic, sudden changes of parameter values in the parameter-sampling and parameter-evolution process, and controls the narrowing of the parameter variance

- Recursively assimilates data into the model, and thus detects the possible time variations of parameters

- Properly addresses various sources of uncertainty stemming from input, output, and parameter uncertainties

In GEMS, the SEnKF procedure becomes regular Monte Carlo analysis at the time steps when no observation data are available for assimilation.

The SEnKF method was tested by assimilating observed fluxes of CO_2 and environmental driving-factor data from an AmeriFlux forest station (located near Howland, Me.) into a model for partitioning eddy-covariance fluxes (Chen and others, 2008). Analysis demonstrated that model parameters, such as light-use efficiency, respiration coefficients, and the minimum and optimum temperatures for photosynthetic activity, are greatly constrained by eddy-covariance flux data at daily to seasonal time scales.

The SEnKF stabilizes parameter values quickly regardless of the initial values of the parameters. Predictions made by SEnKF with data assimilation matched observations substantially better than predictions made without data assimilation (fig. D10). Additionally, this approach also is efficient in finding the optimum parameters (fig. D11).

D.2.6. Input and Output Processor and NetCDF Interface

A GIS program (JFD Builder) was developed for generating a JFD table from primary input data layers. A NetCDF program (called NCWin) for processing and visualizing NetCDF data also was developed. All mapped data (for example, climate, soil, vegetation cover, disturbance events) are saved in NetCDF format in GEMS. The NCWin graphical user interface (GUI) provides the capability to convert and visualize input and output maps as well as temporal data trends (fig. D12).

D.3. Integrating With Other Models

D.3.1. Linkages With Land-Use- and Land-Cover-Change Data and Projections

For the national assessment, GEMS will be directly coupled with the land-use-change model FORE–SCE (appendix B of this report) to account for the effects of past land-cover and land-use changes and simulated future land-use changes on ecosystem carbon-nitrogen dynamics. LULCC maps generated by the model will be used to produce spatial simulation units either by the JFD approach or a land pixel sampling approach. For an individual plot, an LULCC file, called the "event schedule file," will be created. This file specifies the type and timing of any LULCC events, as well
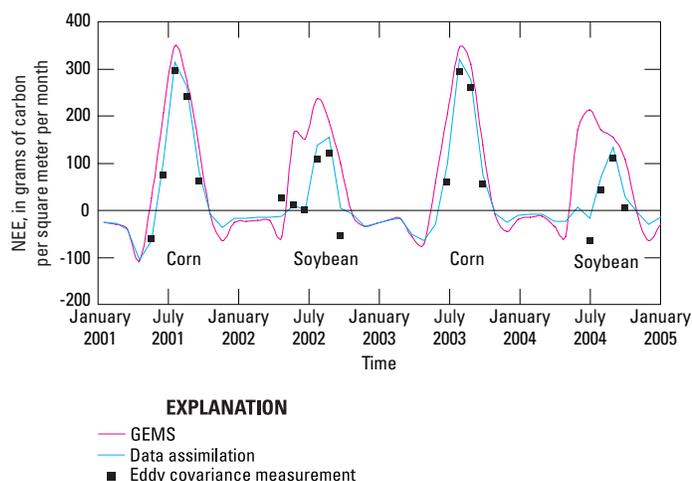
A
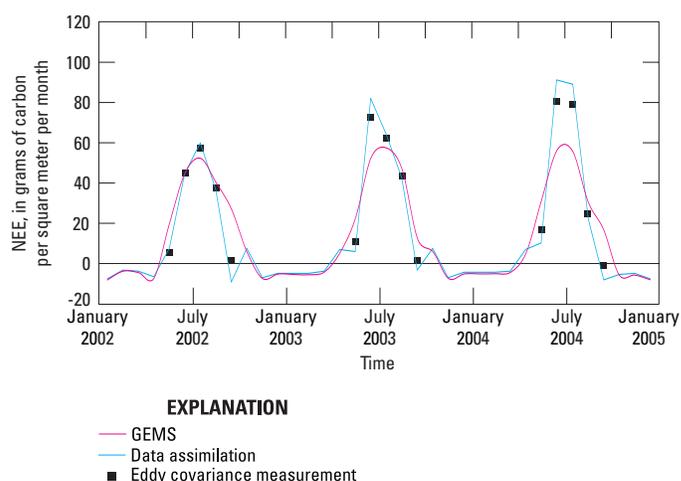
B

Figure D10.   Graphs showing an example of Smoothed Ensemble Kalman Filter (SEnKF) data assimilation on state variables. The "GEMS" curve represents the GEMS model without data assimilation. The "Data Assimilation" curve represents the GEMS model with data assimilation. Field observations (red squares) are from the online data archive of American Flux Network (AmeriFlux) sites.
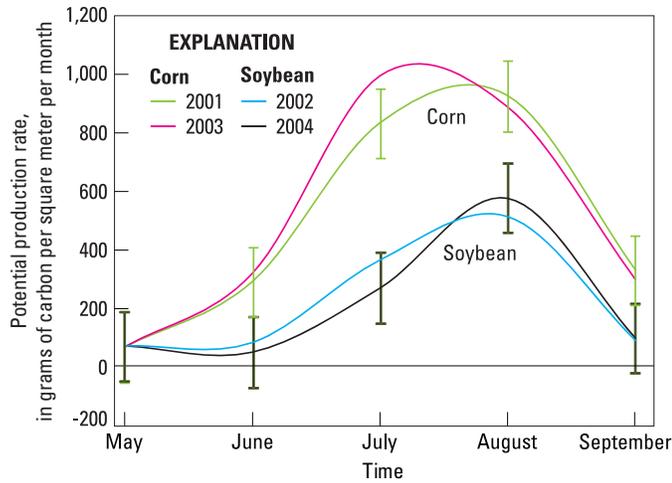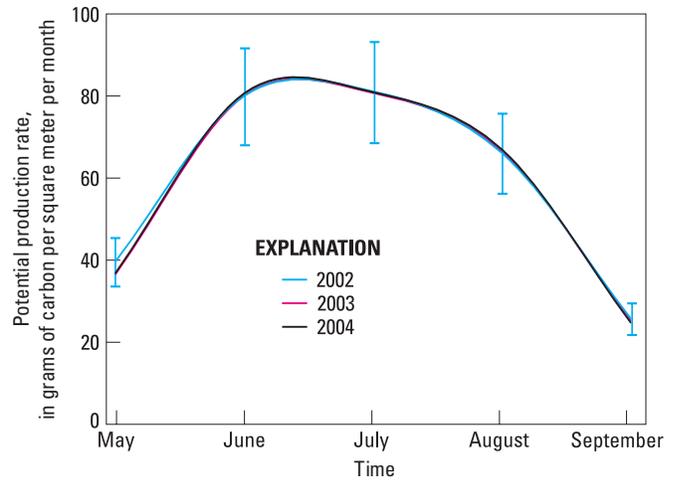
A   **B**

Figure D11.   Graphs showing the results of parameter estimation for the plant-production submodel using the Smoothed Ensemble Kalman Filter (SEnKF) in the biogeochemical General Ensemble Modeling System (GEMS). The graphs show seasonal variations of the potential plant-production rate in croplands (left) and in forests (right). The seasonal variations imply that the structure of the plant-production model might not be adequate to represent the seasonality of crop growth.


B

A
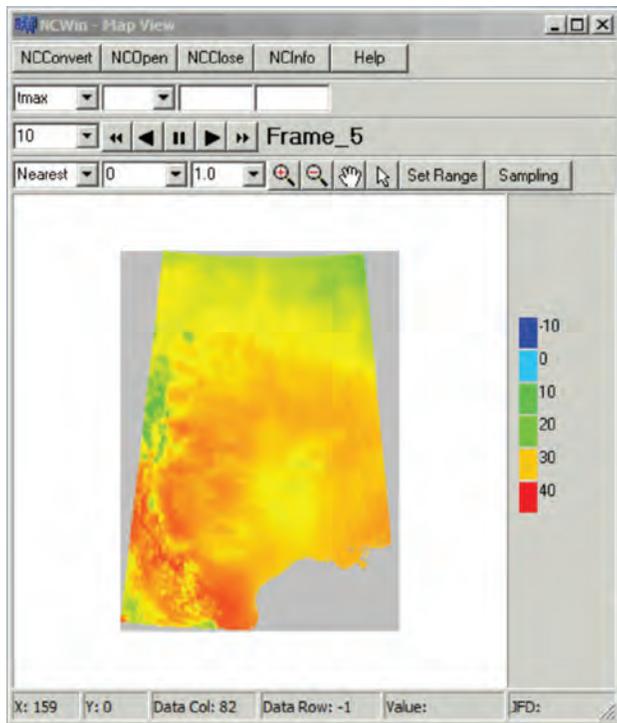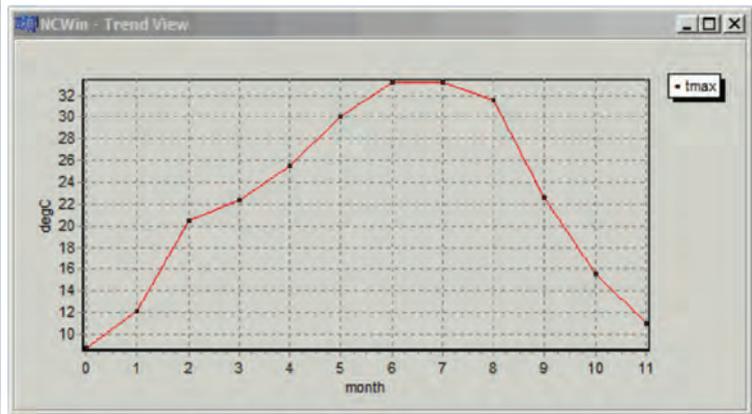
Figure D12.   Screen capture showing an example of the NCWin map and data trends graphical user interface.

as the type and timing of management practices, such as cultivation and fertilization.

The LULCC information from the land-change model and other information (for example, the USDA Natural Resources Inventory (NRI) database) will be assimilated using the following procedures:

- Events such as forest clearcutting, deforestation, urbanization, and reforestation will be directly incorporated. A biomass removal or restoration algorithm will be applied to land pixels with these land-use-change events.

- Although annual clearcutting events will be provided by the land-change model, selective cutting events (for example, group-selection harvesting and fuel treatment) are not available. The selective cutting activities can be scheduled based on selective cutting rates derived from other sources, such as FIA databases, the new vegetation change tracker (VCT) product derived from LANDFIRE (Huang and others, 2009), and forest fuel-treatment data. GEMS can aggregate the total selective cutting area to an equivalent amount of clearcutting area and randomly assign the derived clearcutting to the forest landscape. GEMS also will calculate specific thinning effects on biomass and soil carbon change when related publications and field data are synthesized.

- Mapping crop species distribution and rotations for large areas is still a primary challenge for national land-cover database development. Crops are aggregated into broad categories (for example, row crops, and other agricultural land). It is necessary to downscale aggregated classes into specific crops for biogeochemical modeling because dif-

ferent crops have different biological characteristics and management practices, likely resulting in different effects on carbon dynamics in vegetation and soils. Disaggregation of the agricultural land data is done stochastically in GEMS based on crop composition statistics at a district or county level. For example, in the U.S. Carbon Trends Project (Liu, Loveland, and Kurtz, 2004; Tan and others, 2005; Liu and others, 2006), schedules of cropping practices, including shares of various crops and rotation probabilities, were derived from the NRI database developed by the USDA Natural Resources Conservation Service. The NRI database is a statistically based sample of land-use and natural-resource conditions and trends on non-Federal lands in the United States. The inventory, covering about 800,000 sample points across the country, is done once every 5 years. Management practices, such as cultivation and fertilization, are incorporated into the LULCC sequences generated for the site according to crop or forest types and geographic region.

D.3.2. Linkages With Aquatic and Wetland Systems

The carbon and nitrogen fluxes within the aquatic ecosystems of wetlands, lakes, rivers, and streams, as well as their lateral interactions with the terrestrial ecosystems and vertical exchanges with the atmosphere, will be quantified within the integrated framework of GEMS through an encapsulated aquatic biogeochemical model. A general framework for the aquatic model, which is primarily developed at the site scale, is presented in figure D13.
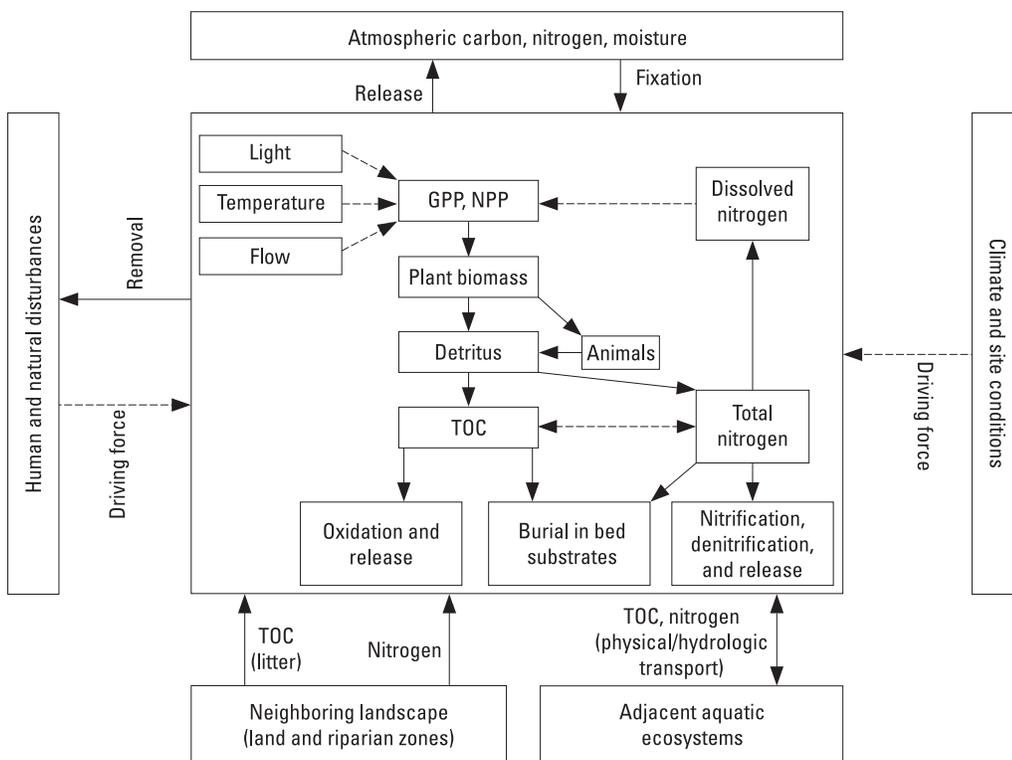

Figure D13. Diagram showing a simplified conceptualization of carbon (C) and nitrogen (N) fluxes, as well as their controls and driving forces, for an encapsulated aquatic biogeochemical model in GEMS. Solid arrows indicate mass flow and dashed arrows indicate controls or driving forces. Abbreviations are found in "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report.

The primary methodology related to aquatic and wetland systems is described in section D.2.1.7 and appendix E of this report. This subsection focuses on the geospatial aspects and heterogeneity of wetland conditions and processes for large areas. Wetlands are important systems that likely play a pivotal role in the sequestration or release of GHG gases. Physical processes such as the hydrology of flooding (which often is intermittent) and associated soil saturation can be considered as some of the common, principal drivers of wetland biogeochemistry. A functional wetland ecosystem can be conceptualized by interactions among the four major components of water, nutrients, habitat (plants and soils), and animals. A schematic diagram of these functional components and interactions is shown in figure D14.

Given the wide variety of coastal and inland wetlands and the wide range of biophysical and climate conditions across the country, it is very difficult to simulate the hydrological dynamics (for example, water-table position) for individual wetlands over large areas using a purely process-based approach. The major
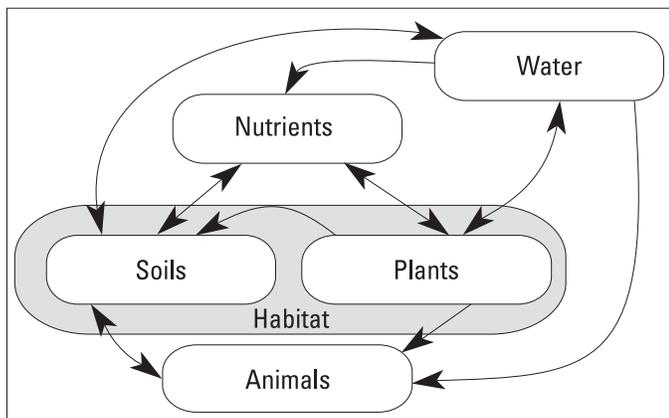
challenges for testing and implementing these models include the limited availability of reliable datasets and proper parameterizations of important driving forces and boundary conditions. To address this challenge, a hybrid modeling approach, combining the process modeling and empirical modeling, is being developed to simulate water storage and water-table dynamics in wetlands. Model simulations will be used to derive relatively robust representations of water storage and water-table dynamics for different types of wetlands, such as permanent to semipermanent and ephemeral to transitional. A frame-based state-transition approach will then be used along with prior knowledge to describe hydrological regimes for different wetlands under various meteorological conditions across the country.

The wetland approach (described in section D.2.1.7 of this report, as well as the river-stream-lake-impoundment methodology in appendix E of this report, will ingest the upland-erosion and organic-carbon data from GEMS as inputs of lateral fluxes from the terrestrial systems. Statistical analyses and findings of the aquatic team can contribute to the calibration, validation, and improvements of the wetland models for realistically simulating the greenhouse-gas fluxes to the atmosphere and evaluating the carbon sequestration of wetland ecosystems.

D.3.3. Feedback Among the Models

Model integration is a critical step in the project because there are time- and space-dependent feedbacks among the different modeling components. For example, FORE–SCE requires information about the site fertility or the SOC level from GEMS to optimize the allocations of crops in space and time. On the other hand, land-disturbance information will affect the land-use behaviors, such as timber harvesting. Without stepwise coupling between FORE–SCE and the disturbances model, timber harvesting activities might still be prescribed in areas where biomass has been completely consumed by fire in the disturbances model. Carbon or biomass stock (fuel load) will strongly affect the probability of fire occurrence and the severity of fires, which requires the coupling between the disturbances model and GEMS, with the latter

Figure D14.   Diagram of conceptual wetland ecosystems and interactions among the functional groups. Modified from Fitz and Hughes (2008), used with permission.
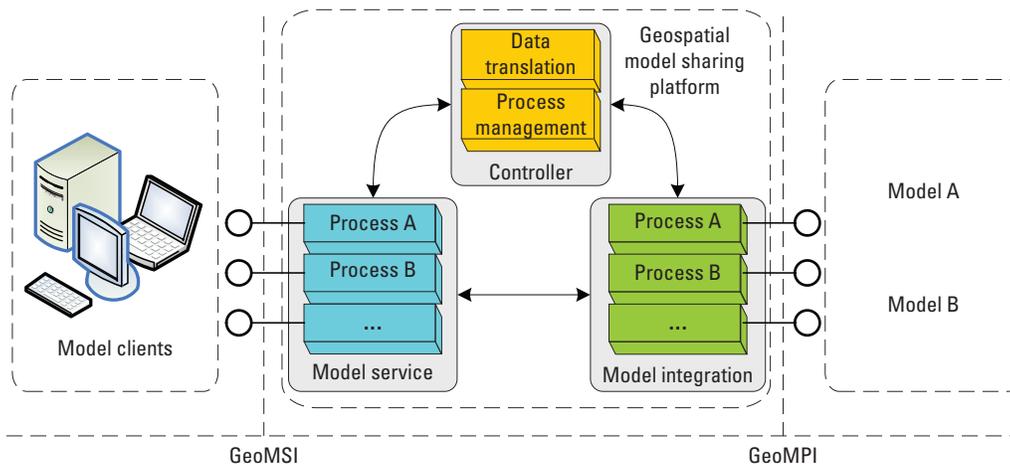

Figure D15.   Diagram showing the system structure of the Geospatial Model Sharing Platform. Modified from Feng and others (2009), used with permission. GeoMPI, Geospatial Model Programing Interface; GeoMSI, Geospatial Model Sharing Interface.

providing carbon-stock information. Model integration will be accomplished on a parallel-processing computer system.

D.4. Relations With Evaluation of Ecosystem Services

Mitigation opportunities that are considered as management scenarios are evaluated with a spreadsheet approach. These opportunities will be modeled using GEMS. Examples of GEMS data products supporting mitigation opportunities (including eco-system-services evaluation) are carbon stocks, CH_4, N_2O fluxes, soil erosion, NPP, wood harvests, surface runoff, and crop yields. In addition, linkages to ecosystem-service evaluation methods (section 3.3.6) will be built based on GEMS output.

The Energy Independence and Security Act of 2007 (EISA) (U.S. Congress, 2007) requires that "short- and long-term mitigation or adaptation strategies" be developed as an outcome of the assessment. In chapter 1 of this report, this was interpreted as a requirement to develop relevant data products and information packages that can be used conveniently by land managers and other stakeholders to develop specific strategies; however, what is "good" from the perspective of one user may be "bad" to another. Land-use change and climate change affect a myriad of ecosystem services simultaneously; some identified specific ecosystem services may be misleading because the overall effect on the ecosystem is not evaluated. Hence, a broader perspective and context is needed to evaluate and understand concurrent effects on multiple ecosystem services. To solve this problem, a platform will be established to project changes in ecosystem services to support adaptive land-management practices. This provides a spatially explicit platform that can accommodate a diversity of land uses and climate change for simultaneous evaluations to better understand biophysical response and tradeoff analyses, highlighting relative effectiveness and efficiency of management activities.

A distributed geospatial model-sharing platform (fig. D15) will be used to model ecosystem services and provide decision support. This platform is necessary to facilitate sharing and integrating geospatial disciplinary models. A platform based on Java Platform Enterprise Edition (J2EE) and open-source geospatial libraries (Feng and others, 2009) is in development. Shared models on the platform are accessible to applications through the Internet using the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard (fig. D16).

Assessment results related to the evaluation of ecosystem services, such as soil erosion and deposition, biomass production, CO_2 emission, and GHG flux, will be evaluated
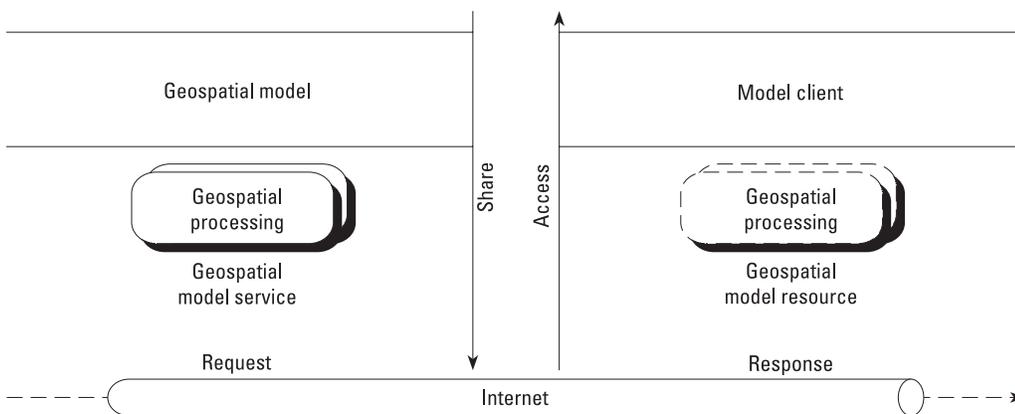
**Figure D16.** Conceptual flow diagram illustrating access to the shared geospatial model. Modified from Feng and others (2009), used with permission.
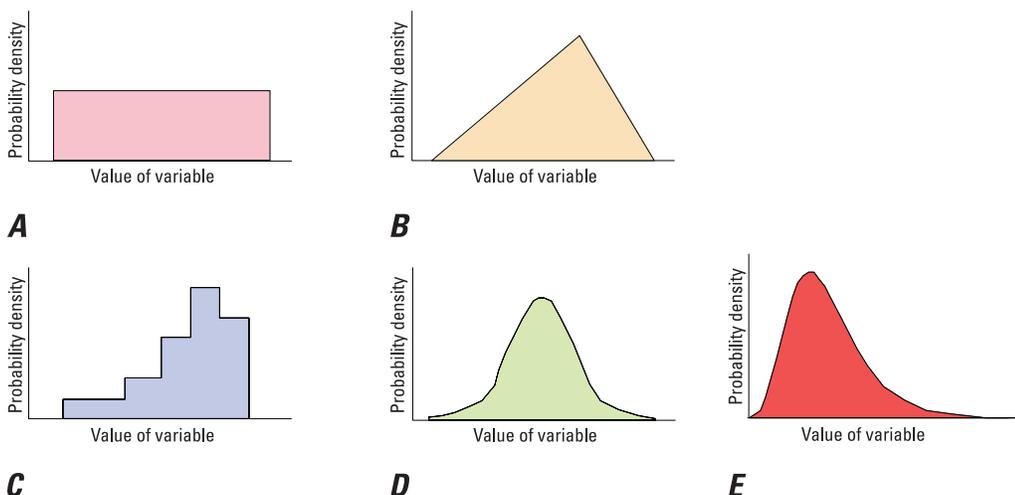
**Figure D17.** Typical probability distribution (density) function (PDF) curves. *A*, Uniform; *B*, Triangle; *C*, Fractile; *D*, Normal; *E*, Lognormal. Modified from Intergovernmental Panel on Climate Change (2006, p. 3.25), used with permission.

and distributed using the model-sharing platform (fig. D15). For a specific region and specific interest, however, numerous submodels can be added to reflect the relative effectiveness and efficiency of management activities. For example, water quantity and water quality, which are important indices of ecosystem services, are increasingly affected by natural and anthropogenic activities. The widely used Soil and Water Assessment Tool (SWAT) can be used to estimate the land-phase processes (for example, surface runoff, soil erosion, nonpoint-source nutrient loss, groundwater recharge, and baseflow) and water-phase processes (for example, water routing, sediment transport, and nutrient transport and its fate in the aquatic systems). GEMS will link with SWAT to assess the climate-change effects on water availability, and sediment and nutrient transport for the landscape. A pilot platform, named EcoServ (ecosystems services model), was developed in the Prairie Pothole region (PPR) to simulate the diversity of ecosystem services simultaneously at landscape scale.

D.5. Estimating Uncertainties

Uncertainty estimates can be in the form of estimated percent errors, standard deviations, confidence intervals, or any other relevant coefficient (Larocque and others, in press). For the assessment, an overall approach to assessing uncertainties is presented in appendix G of this report. Here, a brief discussion is presented about how uncertainties related to GEMS data, parameters, and model structure will be handled.

Following the IPCC (2006) guidance, uncertainty analysis mainly focuses on random errors. Model bias removal will be based on model calibration with in situ data.

The factors to be considered in the uncertainty evaluation should have an uncertainty range, either expressed as a probability distribution function (PDF) curve or a probability look-up table. Typical PDFs described by IPCC (2006) are shown in figure D17. In GEMS, uncertainty factors may include forest age, crop species, soil type, canopy density, logging location, burn severity, and agricultural management.

If a model parameter has a PDF, it can be evaluated using error propagation. When a parameter PDF is not available, it is possible to derive the PDF using a data-assimilation technique. Some parameters may be obtained from expert judgment, which also has uncertainties.

The IPCC error propagation equation(s) will be used to aggregate the uncertainty from different vegetation types (such as forest or crop) to the JFD level, and aggregate uncertainty from the JFD level to a region:

Table D3.   Preliminary methods or models to be used to assess parameters of carbon stocks, carbon sequestration, and greenhouse-gas fluxes by ecosystems defined for the assessment.

[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 in the assessment. Input data requirements for each ecosystem are also listed. An explanation of abbreviations and acronyms is found in "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report]

Methods	Deliverables	Technical processes	Target ecosystems	Data needs or sources
Spreadsheet	C_s, C_{sr}, CO_2, N_2O, CH_4	Algorithms based on storage-age growth curves	Forests Urban forests Grasslands/shrublands Croplands Wetlands	Growth curve from FIA, crop production from NRCIS, NWI, local and IPCC standard GHG emission factors, GRACEnet data.
EDCM	C_s, C_{sr}, CO_2, N_2O, CH_4, Carbon and nitrogen leaching, erosion, and deposition	Maximum potential productivity, monthly time step, spatial sampling, and ensemble simulation Parameterizations based on Cao and others (1996), Liu and others (1999), Parton and others (2001)	Forests Urban forests Grasslands/shrublands Croplands Wetlands	LULCC, current climate, IPCC GCM projections, USDA census data, disturbance (fire, drought, and so on), hydrological model inputs (soil erosion, deposition), management data (grazing intensity, fertilizer application), SSURGO soil data, GRACEnet data.
Century	C_s, C_{sr}, CO_2, N_2O, CH_4, Carbon and nitrogen leaching	Maximum potential productivity, monthly time step, spatial sampling, and ensemble simulation	Forests Urban forests Grasslands/shrublands Croplands	LULCC, topography (DEM), current climate, IPCC GCM projections, USDA census data, disturbance (fire, drought), hydrological model inputs (soil erosion, deposition), GRACEnet data.
IBIS	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 Grasslands/shrublands Croplands	LULCC, topography (DEM), current climate, IPCC GCM projections, USDA census data, disturbance (fire, drought), hydrological model inputs (soil erosion, deposition).
USPED	C_{ed}	Empirical two-dimensional algorithm	Forests Grasslands/shrublands Croplands	Link with EDCM, SSURGO K factor, SRT DEM data, LULCC, precipitation from climate data (current and future projections).
Zero-dimensional model	CH_4, CO_2 N_2O,	Process-based, simple framework, compatible in large-scales Parameterizations using Cao and others (1996), Li and others (1992), Potter (1997), Walter and others (2001), Zhuang and others (2006), and Hénault and others (2005)	Wetlands	Link with EDCM, NWI, SSURGO, NCDC, NLCD, regional wetland database, GRACEnet data.

$$U_{total} = \frac{\sqrt{(U_1 \times x_1)^2 + (U_2 \times x_2)^2 + ... + (U_1 \times x_1)^2}}{|x_1 + x_2 + ... + x_n|}, \quad (D14)$$

where x is area weight, and
        U is uncertainty.

Beyond error propagation, another effective approach to quantify modeling uncertainty is model comparison. Because GEMS can encapsulate multiple models, and parameterize and drive these models with the same data, it provides an ideal environment or platform to identify and address issues and uncertainty related to model structure and mathematical representations of biophysical processes. GEMS eventually will include 5 to 10 BGC models in the national assessment.

D.6. Biogeochemical Deliverables

Major GEMS deliverables generated from various models or approaches are listed in table D3. Most of the outputs can be summarized in tables and displayed in map series.

D.7. References Cited

[Reports that are only available online may require a subscription for access.]

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Appendix E. Methods for Assessing Carbon Stocks, Carbon Sequestration, and Greenhouse-Gas Fluxes in Aquatic Ecosystems

E.1. Introduction

Inland and coastal waters are globally important locations of biogeochemical carbon cycling, carbon sequestration, and the exchange of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) with the atmosphere. Although inland aquatic ecosystems represent less than 3 percent of the total land area of the United States, they have greatly accelerated areal rates of carbon cycling relative to terrestrial ecosystems and may dominate greenhouse-gas (GHG) fluxes and carbon sequestration locally and regionally. Globally, the mass of carbon exported by inland waters to oceans annually rivals the terrestrial net ecosystem exchange (NEE; Sarmiento and Gruber, 2006), and the annual amount of carbon buried in inland water sediments is comparable to that of the annual amount of carbon buried in coastal ocean sediments (Cole and others, 2007). When evaluating the importance of coastal, estuarine, and inland waters in the carbon cycle, three major factors should be considered:

- Stream and river delivery of inorganic carbon (IC) and organic carbon (OC) from terrestrial uplands; through lowlands, ponds, lakes, and reservoirs; and to coastal areas and oceans (termed "lateral transport")

- Biogeochemical production, consumption, sequestration, and pass-through of dissolved, particulate, and gaseous carbon by ponds, lakes, and reservoirs

- Biogeochemical production, consumption, sequestration, and pass-through of dissolved, particulate, and gaseous carbon by coastal waters and estuaries

The importance of inland waters in the carbon cycle tends to be overlooked in terrestrial ecosystem models and global climate models, partly because of their size. Most water bodies are much smaller than the individual grid cells used as accounting units for regional-scale models. This problem is compounded by the fact that the numbers of water bodies increase exponentially as water-body size decreases (Downing and others, 2006) and that rates of carbon sequestration (Downing and others, 2008) and carbon-gas exchange, particularly methane emission (Michmerhuizen and others, 1996), are thought to increase as water-body size decreases. Consequently, if a water body is large enough to be detected at the pixel scale for terrestrial ecosystem modeling, the rates of carbon sequestration and carbon-gas exchange associated with

that water body are likely to be smaller than global or regional averages. For these reasons, accurate regional modeling of carbon sequestration and gas exchange currently (2010) requires (1) independent assessment of the lateral flux of carbon to and from those regions, (2) an accurate accounting of the areal extent and size distribution of the water bodies within those regions, and (3) the assignment of regionally explicit biogeochemical rates of carbon sequestration and gas exchange that encompass the size distribution of streams, rivers, ponds, lakes, and reservoirs within those regions.

The carbon mass balance of estuaries and coastal areas of the Nation also is poorly quantified. Estuaries and coastal areas are some of the most biologically productive areas of the world, and the delivery of terrestrial carbon and nutrients to them by lateral flux and coastal erosion substantially enhances that production. In addition, local currents, temperature, bottom slope, and biogeochemical reactions all affect the quantity and form of particulate and dissolved carbon that will be sequestered in coastal areas, passed through to oceans, or converted to greenhouse gases and emitted to the atmosphere. These and many other physical, chemical and biological factors controlling carbon cycling in near-shore areas vary substantially with space and time, complicating a national assessment of carbon sequestration and flux. Processes in coastal areas often are overlooked or underestimated in ocean carbon-cycling models because ocean models normally are operated at relatively coarse spatial resolution, and inclusion of coastal pixels confounds remotely sensed data and model execution (Dunne and others, 2005, 2007). Because coastal areas represent the confluence of terrestrial and oceanic processes, most ocean carbon sequestration occurs in the coastal zone, and terrestrial processes may dramatically alter coastal and estuarine processes; therefore, the impacts of terrestrial management actions and carbon processes in the coastal ocean should be carefully examined (Hedges and Keil, 1995; Seitzinger and others, 2005). Because of coastal groundwater discharge, carbon fluxes also have received relatively little attention, but Cole and others (2007) estimated that, globally, groundwater conveys dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) loads making up about 25 percent of the total carbon flux from land to sea.

The sections that follow present a methodology for a national assessment of the lateral flux of carbon, carbon sequestration, and GHG exchange associated with inland and coastal waters. Methods are proposed for projecting the assessment into the future to account for ongoing and anticipated land-cover and climate change. In this report, aquatic carbon is grouped into four general categories:

- DOC, which is composed of all the dissolved fraction of organic carbon molecules that result from the production and decomposition of living matter (dissolved is operationally defined as the fraction that passes a 0.45 or 0.2 micrometer filter)

- DIC, which is composed of the aqueous carbon anions bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}), carbonic acid, and dissolved CO_2

- Particulate organic carbon (POC), which is composed mostly of plant and animal debris, but also includes organic colloids, precipitates, and DOC adsorbed to particle surfaces

- Particulate inorganic carbon (PIC), which is composed of mechanically eroded sediments derived from carbonate rocks and carbonate precipitates

DOC and DIC represent most of the total carbon mass in lateral flux, whereas POC and PIC represent most of the carbon stored in inland waters and coastal sediments. Except in areas where old DOC is released from the terrestrial environment (such as from petroleum hydrocarbons, glacial melt, or permafrost thaw), most DOC tends to be modern in age and represents recently produced photosynthate that is leached from decomposing plant debris and soil organic matter. DIC is produced primarily by weathering of carbonate and silicate rocks and fine particles, where one-half of the carbon in DIC produced by carbonate weathering and all of the carbon in DIC produced by silicate weathering is derived from ecosystem respiration or atmospheric CO_2, and is therefore modern. The DOC and DIC exported from terrestrial landscapes are largely unaccounted for in terrestrial NEE or net ecosystem production (NEP) measurements, but regionally they may represent more than 5 percent of total ecosystem production (Striegl and others, 2007). POC includes recently produced plant and animal debris and some older organic carbon debris that has eroded from landscapes and is carried by water. POC that settles to streambeds or lake bottoms may serve as a food source for grazing organisms and microbes or be sequestered. Except for lakes and ponds having recent precipitation of carbonates, PIC plays a relatively unimportant role in the sequestration of modern carbon, as it mostly includes carbon from old marine carbonates.

E.2. Transport of Carbon by Streams and Rivers

E.2.1. Lateral Flux

Lateral (or hydrologic) flux of carbon includes the delivery of dissolved and particulate carbon by streams and rivers from terrestrial landscapes to inland water bodies, coastal waters, and oceans. Flux also includes delivery of dissolved carbon by groundwater discharge to inland water bodies and coasts. Water is the carrier of all lateral carbon flux; therefore, the direct calculation of lateral carbon flux requires a quantitative understanding of water discharge and of the seasonal relations between water discharge and the concentrations of

the aqueous carbon species (DOC, DIC, POC, PIC) that are transported. Inferential methods for estimating carbon flux based on land-cover characteristics and hydrologic-systems modeling of flow based on geomorphic and climatic conditions are promising, but currently (2010) are not fully coupled with carbon chemistry. The most accurate way to assess lateral flux, therefore, is to develop statistical relations between historical flow and chemistry data, and then empirically derive daily loads (mass carbon per time) for each carbon species (Striegl and others, 2007). There are multivariate statistical programs, such as the U.S. Geological Survey (USGS) Load Estimator (LOADEST) program, which are designed to do this for streams and rivers (Runkel and others, 2004). Estimates of groundwater flux are less accurate because groundwater-flow rates and chemistry generally are not measured; however, groundwater contributions to total carbon flux for large areas, such as the coastal United States, can be assumed to be small relative to surface-water flux.

E.2.2. Estimation of Lateral Flux

The LOADEST program (U.S. Geological Survey, 2010b) associates daily water-discharge values with constituent concentrations measured for a range of discharge conditions and develops statistical concentration-to-discharge relations for the constituent of concern. Based on these relations, LOADEST simulates concentrations for days without measurements, and then integrates discharge and concentration to estimate the total constituent load for the analyzed flow period. The accuracy of the estimates depends on the accuracy of the water discharge and constituent concentration measurements, adequate coverage of concentration measurements for a full range of flow conditions and seasons, and stability in concentration-to-discharge relations. Generally, at least 13 concentration measurements are required for LOADEST to produce accurate estimates; more are better, especially where concentration discharge relations vary seasonally. Sample collection during storm events is particularly important because most suspended sediment is transported during storms (Cohn and others, 1989; Hicks and others, 2000). If the LOADEST program is applied for estimating lateral flux from streams and rivers that have not been measured by streamgages or sampled for concentrations of carbon species, the accuracy will be degraded based on additional uncertainties associated with the regression techniques for estimating discharge and carbon concentration in those rivers.

The "spatially referenced regressions on watershed attributes" (SPARROW) model (U.S. Geological Survey, 2010e) uses these same techniques to estimate constituent loads (Schwarz and others, 2006, 2008). This model has the additional advantage of generating flow and concentrations based on land-use and land-cover characteristics and climatic data. SPARROW has been used extensively for estimating nitrogen and phosphorus loads and currently (2010) is under development for estimating carbon species, particularly DOC. Additional details on the SPARROW modeling approach are described in section E.4.3 of this report.

E.2.3. Data Needs and Availability

Estimating carbon loads requires both flow and water-chemistry data collected at identical or close locations during identical periods. These data are archived in the National Water Information System (NWIS; U.S. Geological Survey, 2010f). Nationally, the USGS has collected data on daily streamflow at more than 25,000 sites and periodic flow information at more than 45,000 sites. Water-chemistry data are sparser—only about 200 stations have more than 10 years of records for flow, DIC, and DOC concentration data. There are many more sites having shorter or partial records.

A first step in the assessment of lateral carbon flux is to extract data from NWIS at locations where streamflow, and DIC, DOC, POC, or PIC data have been collected. These data will be assembled into a working database for further analysis. Carbon-concentration data are most prevalent for carbonate alkalinity, from which DIC can be calculated, followed by DOC, POC, and PIC. For organic carbon, older datasets commonly have only total organic carbon concentration (TOC), which by definition is DOC + POC, but operationally is commonly closer to DOC. Where concentration data are missing for a particular carbon species, it will be necessary to statistically estimate concentrations from other available water-chemistry data.

E.2.4. An Approach for the Nationwide Assessment of Lateral Flux

A key step in the data analysis will be to identify key streamgaging stations from throughout the United States where carbon loads can be calculated and carbon concentration-to-discharge relations can be established. These key stations will represent large aggregated basins that drain directly to coastal areas, such as the Mississippi River and Columbia River Basins (fig. E1), and smaller basins that represent specific land-use or land-cover types and (or) ecoregions. Basins of the conterminous United States are mapped in four orders of hydrologic units, including 18 regions, 204 subregions, 324 accounting units, and 2,111 cataloging units (U.S. Geological Survey, 2010a). Alaska, Hawaii, and Puerto Rico are similarly divided. Approximately 308 hydrologic units drain directly to coastal areas of the United States, ranging from a few tens of square kilometers to the Mississippi River Basin. The assessment eventually will assign carbon lateral-flux values to all of these units.

Seasonal and annual loads (mass of carbon over time) and yields (mass of carbon over basin area over time) will be determined for the key streamgaging stations using LOADEST and SPARROW. The mass flux of carbon is primarily determined by water discharge, so concentration-to-discharge and carbon yield-to-water yield relations also will be determined.
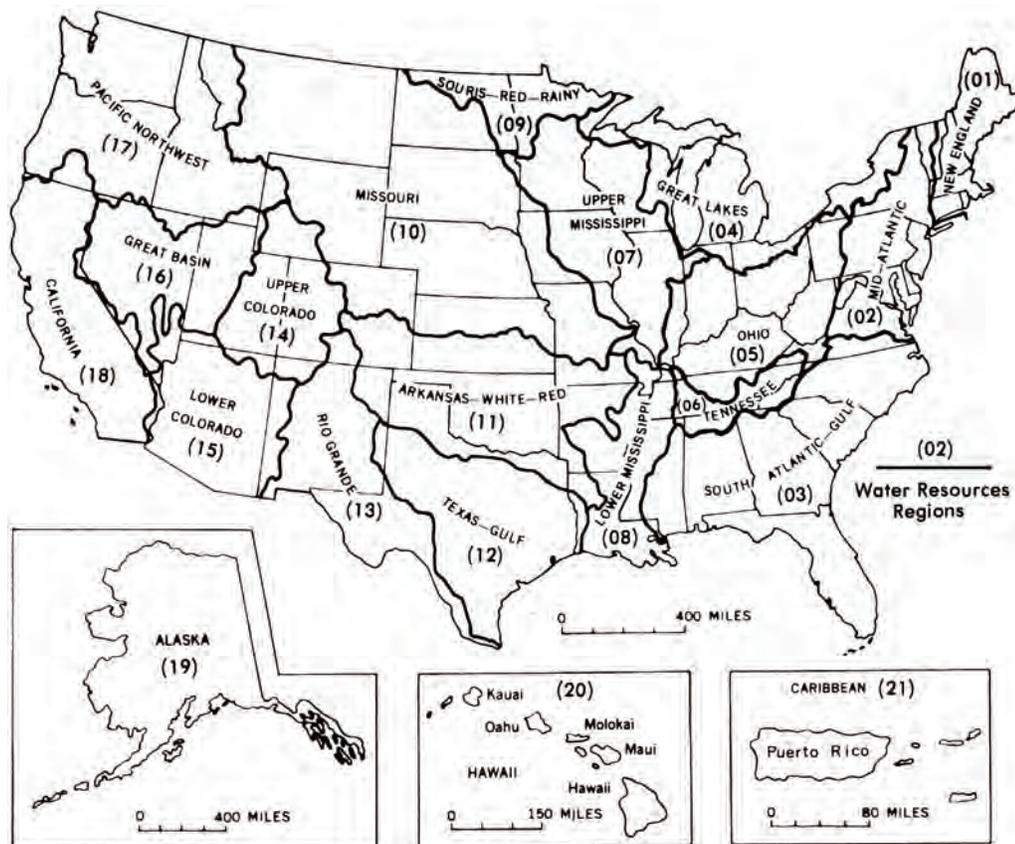
Figure E1.   Map showing the water-resource regions of the United States that will be used as units for aquatic assessment (rivers, lakes, coastal regions). From Seaber and others, 1987, figure 2.

These relations will be used for gap analysis to estimate fluxes from adjacent basins that are missing carbon-concentration data. Regression techniques will be used to estimate discharge for ungaged basins that are likely to transport substantial carbon to the coast, as discussed in Hirsch and others (1982).

E.2.5. Coupling of Lateral Flux With Terrestrial Models

Currently (2010), the General Ensemble Modeling System (GEMS) and other terrestrial ecosystem models solve the carbon mass balance in one-dimensional grid cells; they do not solve for the lateral flux of water and carbon between cells. One goal of this assessment is to couple hydrologic and terrestrial models so that water discharge and carbon flux can be estimated on the basis of land use, land cover, physiography, and climate. The NWIS, LOADEST, and SPARROW analysis of lateral carbon flux will provide empirical validation for the development of these model attributes.

E.2.6. Projections of Lateral Flux

Water discharge is the primary determinant of lateral carbon flux from basins, and therefore needs to be accurately projected for estimating future carbon later flux. Estimating future lateral flux will require the projection of water discharge from downscaled climate predictions and the application of flow-generation models, such as the Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983; U.S. Geological Survey, 2010d). Developing relations between lateral carbon flux and land use and land cover (LULC) and coupling these relations with GEMS or models such as SPARROW will further refine these projections. Developing such modeling capabilities should be a goal for future assessments.

E.2.7. Greenhouse-Gas Fluxes From Rivers

In addition to the downstream transport of dissolved and particulate carbon, streams and rivers commonly are supersaturated with CO_2 and CH_4 relative to the atmosphere and emit GHGs to the atmosphere along their entire courses (Cole and others, 2007). The high concentrations of CO_2 and CH_4 can be attributed to within-stream biological cycling of carbon (Ritchie, 1989) and to supersaturated groundwater and surface runoff that contributes to streams and rivers.

E.3. Lakes and Impoundments

Inland waters are an important component of the global carbon cycle but often are ignored in global climate models because they make up only a small part of the surface of continents (about 3 percent ; Downing and others, 2006). Recent studies have shown, however, that fluxes of carbon from terrestrial to aquatic systems are substantial; for comparison, they are similar in magnitude to the NEP of the terrestrial biosphere (about 2 petagrams of carbon per year (PgC/yr)), and thus should not be ignored in global carbon budgets (Randerson and others, 2002; Cole and others, 2007). Although inland waters make up only a small fraction of the total continental area, they are extremely active in the transport and storage of carbon received from the terrestrial environment (Cole and others, 2007; Tranvik and others, 2009). Pools of carbon stored in freshwater sediments also are large; approximately 820 petagrams of carbon (PgC) were stored in lake sediments during the Holocene (Einsele and others, 2001), which is comparable to the amount of carbon currently (2010) stored in the surface meter of soils (approximately 1,395 to 1,576 PgC) and terrestrial biomass (approximately 460 PgC) (Post and others, 1982; Raich and Schlesinger, 1992; Eswaran and others, 1993).

Humans have had a profound effect on hydrologic systems and sediment transport during the last several hundred years. Two of the main human activities that have affected the lateral flux of carbon are (1) deforestation in order to clear the land for tilled agriculture (causing increased erosion) and (2) the construction of dams to form impoundments (Mann, 1985, 1986; Davidson and others, 1993; Paul and others, 1997; Renwick and others, 2005). Impoundments (such as reservoirs and ponds) serve many functions; reservoirs commonly are used for hydroelectric power generation, recreation, flood control, and storing water for drinking and irrigation; ponds are smaller impoundments (usually less than or equal to 1 square kilometer) that typically are used for sediment retention, urban stormwater control, or providing water for livestock. Impoundments alter the hydrologic system by capturing sediment that previously was carried in suspension by streams and rivers and storing it in pools of slow-moving water, where it settles out and accumulates (Meade, 1982; Stallard, 1998). This alteration represents a substantial diversion of sediment that previously was exported to the ocean; it is estimated that impoundments can store about 50 percent of erosion products (Smith and others, 2005).

Organic matter makes up a small but important fraction of material that is eroded from upland areas and redeposited in colluvium or alluvium, or downstream in lakes or impoundments; in the Mississippi River Basin, for example, the average soil organic carbon content is 1.5 percent in erosional and depositional areas (Smith and others, 2005). Most organic carbon that is deposited in impoundments remains there for the life of the impoundment (tens to hundreds of years) because impoundment sediments usually are anoxic, which prevents oxidation of the organic matter (Tranvik and others, 2009); thus, burial of organic carbon in impoundment sediments can represent an important mechanism for carbon sequestration. Lakes can sequester organic carbon by burial as well; however, most of the carbon that is buried in lakes is autochthonous material that is produced by phytoplankton and aquatic macrophytes in the lake (Dean and Gorham, 1998). Tranvik and others (2009) estimated that global burial of organic carbon in lakes and impoundments may account for 0.6 PgC/yr. This estimate compares well with organic carbon burial rates in oceans of 0.1 PgC/yr (Dean and Gorham, 1998)

and with the net uptake of carbon by the terrestrial biosphere of 1 to 3 PgC/yr (Sundquist, 1993).

Burial rates for organic carbon in lakes and impoundments are inversely related to water-body size (Smith and others, 2002; Downing and others, 2008) because of the increased productivity in shallow eutrophic ponds and the high rates of erosion and sedimentation in agricultural areas, where small farm ponds are common. Although ponds are small, their global extent is sizeable, so their cumulative effect on the global carbon budget could be substantial. Renwick and others (2005) estimated that there may be up to 8 to 9 million ponds in the conterminous United States alone, and their number has been increasing by 1 to 2 percent annually in agricultural parts of the United States (Downing and others, 2006).

Lakes and impoundments emit substantial amounts of CO_2 and CH_4, and small amounts of N_2O to the atmosphere. Global CO_2 and CH_4 fluxes from reservoirs account for 4 percent of total anthropogenic CO_2 emissions and 20 percent of total anthropogenic CH_4 emissions, respectively (St. Louis and others, 2000). The balance between carbon burial and GHG emissions determines whether or not lakes and impoundments are net sinks or net sources of carbon (Hanson and others, 2004). Global emissions of CO_2 from lakes and reservoirs have been estimated at approximately 0.8 PgC/yr (Tranvik and others, 2009); for comparison, deforestation releases 1.6 to 2 PgC/yr (Sundquist, 1993; DeFries and others, 2002; Houghton, 2003; Sundquist and others, 2008). Methane emissions from lakes and impoundments could be even more important than CO_2 in terms of GHG potential. Methane is a powerful GHG that has 25 times the warming potential of CO_2, and accounts for 20 percent of the anthropogenic GHG effect (Cicerone and Oremland, 1988; Wuebbles and Hayhoe, 2002). Global emissions of methane from reservoirs have been estimated to be 70 teragrams of methane per year (TgCH$_4$/yr), which accounts for 7 percent of anthropogenic warming (St. Louis and others, 2000).

Methane emissions from lakes add another 8 to 48 TgCH$_4$/yr to the atmosphere (Bastviken and others, 2004). Together, methane emissions from lakes and reservoirs are similar in magnitude to those from other anthropogenic sources, including fossil-fuel combustion (100 TgCH$_4$/yr), waste management (90 TgCH$_4$/yr), enteric fermentation (85 TgCH$_4$/yr), rice paddy cultivation (60 TgCH$_4$/yr), and biomass burning (40 TgCH$_4$/yr) (St. Louis and others, 2000, and references therein).

The following section describes the methodology for assessing carbon sequestration in and GHG fluxes from lakes and impoundments in the United States.

E.3.1. Estimating the Amount of Carbon Buried in Lakes and Impoundments

The net storage of carbon in lakes and impoundments reflects a balance between the amount of carbon buried in sediments and GHG emissions from the surfaces and outlets of the water bodies. Estimating the amount of carbon buried in lakes and impoundments requires several steps that use a combination of geographic information systems (GIS), remote sensing, and statistical analyses (fig. E2). To determine the amount of carbon buried in lakes and impoundments, it is necessary to quantify the total area of lakes and impoundments within specified size classes, the sedimentation rates, and the organic carbon concentrations in sediments.

The statistical distribution of water bodies within the assessment units (U.S. Environmental Protection Agency (EPA) Level II ecoregions modified from Omernik (1987)) will be analyzed in a GIS framework in order to quantify their number and cumulative area within each of ten size classes (fig. E2). Input datasets will include the National Land Cover Dataset (NLCD) and the National Hydrography Dataset (NHD+). The NLCD is a nationally consistent land-cover classification
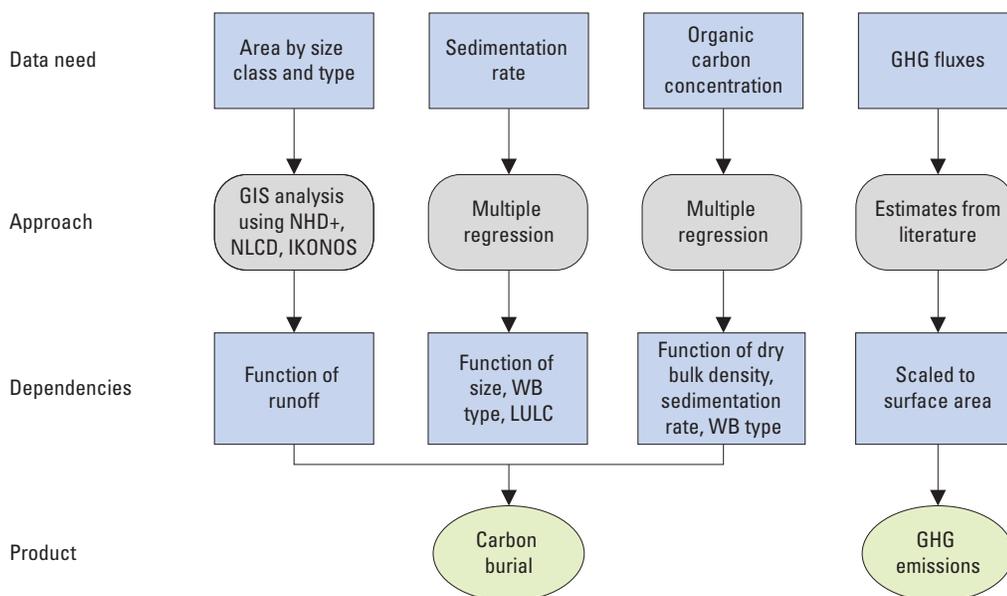

Figure E2. Schematic diagram showing key components of the methodology for assessing carbon sequestration in and greenhouse-gas fluxes from lakes and impoundments. Examples of key dependencies are given. GHG, greenhouse gas; IKONOS, Earth-observing satellite; LULC, land use and land cover; NHD+, National Hydrography Dataset Plus; NLCD, National Land Cover Database; WB, water body.

scheme derived from Landsat Thematic Mapper satellite data and is one of the primary datasets used by other components of the assessment; therefore, it will be the primary dataset used to determine the statistical distribution and surface area of water bodies. The NHD+ is a GIS dataset developed by the USGS that depicts the Nation's interconnected network of rivers, streams, lakes, impoundments, and canals. The NHD+ will be used to validate the information about water bodies in the NLCD. The NLCD and NHD+ datasets display information at 30-meter (m) resolution, which is useful for identifying water bodies larger than approximately 0.001 square kilometers (km^2). Because of the potential importance of carbon cycling in smaller water bodies, the feasibility of mapping those as small as 0.0001 km^2 will be investigated using a variety of techniques and datasets. It may be possible to map small water bodies using a combination of 10-m-resolution digital elevation models (DEMs) and 15-m panchromatic Landsat images, which cover most of the Nation. GeoEye and IKONOS are Earth-observing satellites that provide multispectral images at 2- to 4-m resolution, which can be used to identify water bodies, but the images are not available for the entire United States. Light detection and ranging (LIDAR) data collected using airborne surveys and synthetic aperture radar data collected using the Japanese Earth Resources Satellite 1 (JERS-1) have shown substantial promise in the identification and mapping of small water bodies (Telmer and Costa, 2007), but coverage of the United States is sparse.

The ratio of lakes to impoundments in each assessment unit will be determined by manually classifying a randomly selected subset of 200 water bodies on the basis of a visual inspection of the high-resolution satellite images overlain on the NLCD dataset layers. The lake-to-impoundment ratio will be combined with water-body-area information to estimate the cumulative area of lakes and impoundments within each assessment unit. This information is needed because lakes and impoundments tend to have different sedimentation rates and sediment organic carbon concentrations, which in turn reflect differences in land use, autochthonous production, and other processes.

An important task for estimating the amount of carbon buried in lakes and impoundments is to quantify the sedimentation rates (fig. E2). Relatively few direct measurements of sedimentation rates in lakes and impoundments are available; this is an important data gap that will limit the accuracy of the estimates of buried carbon. Initial estimates of sedimentation rates will be derived from data compiled from published sources and databases; these data will be used to estimate probability distribution functions (PDFs) representing the statistical distribution of measured sedimentation rates, which will be scaled to lake and impoundment surface areas. Most sedimentation-rate data for lakes are from dated lake-sediment cores (Dean and Gorham, 1998; Cole and others, 2007); most sedimentation-rate data for impoundments are from repeated bathymetric surveys. Although there is no central repository for sedimentation-rate data for lakes, sediment-rate data for impoundments are stored in the national Reservoir Sedimentation (RESSED) database (Advisory Committee on Water Information, Subcommittee

on Sedimentation, 2010). The RESSED database includes data from approximately 1,800 reservoirs; however, this is less than 0.2 percent of the total number of impoundments in the United States (Ackerman and others, 2009). Additional data collection on sedimentation rates in lakes and reservoirs could improve the accuracy of this assessment.

It may be possible to improve on the initial sedimentation-rate estimates by using statistical relations between sedimentation rates and water-body size, water-body type (lake versus impoundment), and land use (Wetzel, 1990, 2001; Smith and others, 2001, 2002). Smith and others (2001, 2002), for example, reported that sedimentation rates vary inversely with water-body size and tend to be greater in impoundments than in lakes. Lakes and impoundments in basins with substantial tilled agriculture may be expected to have greater sedimentation rates than those in basins that are largely undisturbed (McIntyre, 1993). Correlations between sedimentation rates, water-body characteristics, and land use will be analyzed for lakes and impoundments in each assessment unit, and if significant relations are identified, multiple regression models will be developed to estimate sedimentation rates for unsampled water bodies throughout the assessment unit. The development of statistical relations in some assessment units may be limited by the scarcity of available sedimentation-rate data. Additional data collection may improve the reliability of the statistical models that are used to estimate sedimentation and carbon-burial rates in unsampled water bodies.

OC concentrations in lake and impoundment sediments reflect the OC concentrations in the upland sediments from which they were derived plus the particulate carbon derived from primary production in the water bodies (Smith and others, 2005). OC concentrations tend to be greater in lake sediments (where autochthonous production is relatively important) than in impoundment sediments (Mulholland and Elwood, 1982; Ritchie, 1989; Dean and Gorham, 1998). OC concentrations in lake sediments will be estimated from data in the literature. If sufficient data exist, then a PDF will be developed for OC in lake sediments; otherwise, a simple median concentration will be used. OC concentrations in impoundment sediments will be approximated by estimating the median OC concentrations in soil in areas that are upslope and within a specified distance from each water body. Soil organic carbon (SOC) concentrations will be derived from a GIS dataset of soil carbon provided by USGS (Bliss and others, 2009). Although it would be preferable to define a basin boundary and estimate SOC concentrations within that area, identifying and mapping basin boundaries for the large number of water bodies in the United States (on the order of 2.6 to 9 million; Renwick and others, 2005) is not operationally feasible. Simplifying the representation of the upslope areas that provide sediment to the downstream lakes and impoundments is likely to reduce the explanatory power of the predictive equations.

The amount of OC buried in lakes and impoundments (OC buried) will be calculated for each size class and type of water body using the following equation:

$$OC \text{ buried} = \text{Total water body area} \times \text{sedimentation rate} \times OC \text{ concentration} \qquad (E1)$$

The sedimentation rates and OC concentrations will be represented by PDFs in the initial analysis. If valid statistical models can be developed for estimating sedimentation rates and OC concentrations on the basis of water-body size and type, they will be used as input to equation E1. The results will be aggregated by EPA level II ecoregion for consistency with other components of the assessment.

E.3.2. Alternate Method for Calculating the Amount of Carbon Buried in Freshwater Aquatic Systems

As a check of the estimates of carbon buried lakes and impoundments (outlined above), the amount of carbon also will be estimated using an independent mass-balance method, as in Smith and others (2005). The method begins with calculating a sediment budget for a river basin and solving for sediment storage (S):

$$E - T = S \qquad (E2)$$

where E is the amount of sediment that is eroded, determined for the basin in GEMS from the two-dimensional Unit Stream Power Erosion and Deposition (USPED) model (Mitas and Mitasova, 1998);

          T is the amount of sediment that is transported to the ocean, calculated in LOADEST from river discharge and suspended-sediment concentrations (Runkel and others, 2004); and

          S is the amount of sediment (including redeposited eroded sediments) that is stored, primarily in alluvium, colluvium, and impoundments.

The amount of sediment exported to oceans is a relatively small component of the equation; Smith and others (2005) estimated that about 90 percent of eroded sediment is redeposited in depositional environments, and about 10 percent is exported to the ocean.

The equation for eroded, transported, and redeposited OC is similar, but requires multiplying each of the terms in the sediment budget equation by the OC concentration (OC percent) of each sediment pool and includes a residual term to account for the oxidation of OC during transport and storage and replacement of eroded SOC in soil:

$$E \times OC \text{ percent} - T \times OC \text{ percent} = S \times OC \text{ percent} \pm \text{residual} \qquad (E3)$$

The right side of equation E3 represents total carbon buried in inland water sediments ± residual. The percentage of OC in the eroded sediment is assumed to be the same as the percentage of OC percent in the redeposited sediment, whereas the percentage of OC in sediment transported to the ocean is approximately twice as high, based on analyses by Ritchie (1989) and Smith and others (2005). The oxidation of OC usually is relatively minor, accounting for about 5 percent of the eroded OC budget (Smith and others, 2005). The replacement of eroded organic matter accounts for approximately 10 percent of the OC budget for the Mississippi River Basin (Smith and others, 2005). These mass-balance calculations provide bounds on the amount of OC that may be stored in inland water sediments, which include lakes and impoundments, as well as fluvial and colluvial systems.

E.3.3. Greenhouse-Gas Fluxes From Lakes and Impoundments

Fluxes of greenhouse gases (CO_2, CH_4, N_2O) from lakes and impoundments will be estimated based on GHG fluxes reported in the literature. Because of the paucity of available data on CH_4 and N_2O fluxes from lakes and impoundments, a PDF approach will be used and emissions will be scaled to lake and impoundment surface areas. This necessarily simplistic approach will have large uncertainties associated with results, but could be refined in the future if sufficient data become available to build empirical models of GHG fluxes, as in St. Louis and others (2000) and Bastviken and others (2004). These studies indicate that GHG emissions from lakes and impoundments are positively related to the area of the lake, which is used as a surrogate for lake depth (Michmerhuizen and others, 1996; St. Louis and others, 2000; Bastviken and others, 2004). GHG emissions also appear to vary with temperature, based on

observations of GHG emissions in the tropics, which were an order of magnitude greater than GHG emissions from temperate reservoirs (St. Louis and others, 2000).

E.3.4. Error Estimation

Uncertainties in estimates of buried carbon in and GHG fluxes from lakes and impoundments will be large because of spatial variability in processes and rates controlling carbon cycling; accounting for this variability using a variety of explanatory variables (for example, basin characteristics or nutrient loads) is difficult in empirical models built on sparse data. In some cases, two independent approaches will be used to estimate fluxes, which can serve as a check of results. The mass-balance calculations, for example, will provide an upper bound on OC buried in lakes and impoundments.

PDFs will be used to represent the statistical distribution of the input data, such as sedimentation rates, OC concentrations in sediments, and GHG fluxes from lakes and impoundments. The spread, or variability, of the input data affects the range of possible outcomes; this range is quantifiable using the PDF approach and will provide information about the uncertainty of estimated carbon burial and GHG emissions rates.

Uncertainty in the empirical models will be evaluated based on the standard errors of the model slopes and intercepts. Bootstrapping or Monte Carlo approaches could be used to evaluate the importance of variations in input datasets to the model results; however, these approaches require a minimum number of observations (for example, 20) to provide meaningful results (Efron, 1981; Efron and Tibshirani, 1993) and it is anticipated that relatively few assessment units will have sufficient data. Additional data collection could allow the use of bootstrapping or Monte Carlo approaches in the future, which would improve the uncertainty analysis.

Uncertainty in sediment and OC mass-balance calculations stems from errors in calculating the sediment and OC fluxes in rivers and in erosion rates (Smith and others, 2005). To accurately estimate the fluxes of sediment and OC in rivers, samples must be collected for a range of hydrologic conditions using appropriate sampling methods. Collecting some samples during storm events is particularly important because most suspended sediment is transported during storms (Cohn and others, 1989; Hicks and others, 2000). Errors in estimated erosion rates are difficult to quantify, but it is assumed the mean standard error of the estimates is near zero (Smith and others, 2001).

E.3.5. Data Needs, Availability, and Gaps

Sedimentation rates and OC concentrations in sediments are key variables for calculating carbon-burial rates in lakes and impoundments, but data are sparse. Measurements of sedimentation rates in lakes are not coordinated at the national level; measurements of sedimentation rates in impoundments are stored in the national RESSED database, but are not collected at a sufficient temporal and spatial resolution to support

an accurate estimate of buried OC for the assessment. It is recommended that these measurements be expanded, a routine monitoring plan be developed, and the RESSED database be used by the U.S. Department of Interior (DOI) and other government agencies as the primary repository for these data.

Despite the importance of GHG fluxes from lakes and impoundments in the global carbon and GHG budgets, measurements are sparse and uncoordinated, and there is no centralized database for these data. Methane emissions from reservoirs may be particularly important, but cannot be quantified at either a regional or national scale with current (2010) information. It is recommended that a Federal monitoring program be initiated to coordinate and conduct GHG flux measurements from lakes and impoundments in support of future carbon assessments.

E.3.6. Projections of Future Fluxes To and From Lakes and Impoundments

Future changes in streamflow, land use, and other management actions have the potential to alter carbon burial in or GHG fluxes from aquatic systems, including lakes and impoundments. Streamflow is a major driver of carbon and nutrient fluxes in rivers, as discussed in section E.2.6 in this report, and efforts are underway to develop models for projecting streamflow and carbon fluxes under various climate-change scenarios.

Management actions can have complex effects, sometimes creating offsetting benefits in terms of carbon sequestration. Land-use conversion from tilled agriculture to no-till or forest, for example, is likely to cause an increase in carbon sequestration on land, but will reduce the amount of carbon buried in lakes and impoundments because of decreased erosion (table E1). Reducing the nutrient runoff from agricultural lands through best management practices (BMPs) will reduce eutrophication and CH_4 and N_2O emissions from inland and coastal waters, but also might cause a decrease in carbon burial because of reduced POC loads in rivers. Understanding the complex effects of these management actions is an area of active research by USGS and others. One goal of the assessment is to add the capability of simulating the effects of these management actions to existing models.

E.4. Coastal and Estuarine Systems

E.4.1. Carbon Sequestration in Coastal and Estuarine Systems

Coastal and estuarine systems are sites where the fluxes of nutrients from terrestrial and deep-ocean sources to the surface of the ocean combine to fuel intense primary productivity. More than 90 percent of global algal productivity occurs in coastal zones (including estuaries), where enough algal carbon is sequestered to make coastal areas important sinks

in the global carbon cycle (Dunne and others, 2007). Coastal areas also are sites that receive riverborne terrestrial exports of particulate and dissolved organic material, a fraction of which is also preserved in coastal-marine sediments or is transported into the deep ocean. Globally, the magnitude of carbon sequestration in coastal oceans is on the same scale as the net terrestrial ecosystem exchange and lateral flux of carbon to the oceans (fig. E3). Because only a small fraction of algal production and terrestrial inputs are preserved, and because coastal upwelling contributes CO_2 from the deep oceans, carbon-preservation processes in coastal oceans may be obscured and difficult to quantify (Hales and others, 2006).

There are two major processes acting to sequester carbon in coastal and estuarine sediments and coastal-ocean waters: direct burial of OC in sediments and particulate transport of OC from the surface to deep oceans (Sarmiento and Gruber, 2002). The latter commonly is referred to as the biological pump. Both processes are strongly related to phytoplankton productivity in the coastal surface oceans, both are coupled to sediment supply from terrestrial systems, and both result in the sequestration of CO_2 from the atmosphere on a decadal to millennial time scale.

Carbon preserved by coastal ocean processes is from autochthonous primary production and from terrestrial inputs. Coastal primary production is fueled by nutrients supplied during terrestrial export, regeneration of nutrients in sediments and the water column, and upwelling of nutrient-rich deep waters. The plankton production supported by externally supplied nutrients—the "new" production—represents potential net removal of CO_2 from the atmosphere. The export of this production into the deep ocean and into coastal sediments is strongly tied to the total production, with higher productivity increasing export (Wassman, 1990). Other factors such as water depth and phytoplankton size also have been linked with export (Dunne and others, 2005), with larger exports observed for populations of large phytoplankton, such as those produced in nutrient-rich coastal areas.

The primary production export from the surface ocean to below the mixed layer—the biological pump—is a major mechanism for carbon sequestration in coastal oceans (Sarmiento and Gruber, 2002; Hales and others, 2006). Primary production in the surface ocean is transported from the mixed layer into the deep ocean as settling particles, with the transported carbon sequestered from free exchange with the atmosphere for periods of decades to centuries, depending on ocean circulation (Sarmiento and Gruber, 2002; Gnanadesikan and Marinov, 2008). Particle flux (POC) has been estimated to range from 0.7 to 1.5 PgC/yr (Dunne and others, 2007; Muller-Karger and others, 2005). Coastal carbon preservation in large measure is, therefore, directly and immediately affected by changes in the export of nutrients from terrestrial systems.

Historical changes in the supply of nutrients to coastal oceans that are related to changes in land use and land cover—such as fertilizer use, increased urbanization, and wetland restoration—likely have altered coastal carbon preservation and will continue to affect coastal carbon preservation to a greater degree in the future (Billen and Garnier, 2007; Seitzinger and Mayorga, 2008). There also is abundant evidence suggesting that submarine groundwater discharge contributes significant amounts of nutrients to coastal systems (Slomp and Van Cappellen, 2004), which is comparable to the nutrient loads delivered by surface water in some watersheds with large nitrogen-loading rates and permeable soils (for example, Valiela and others, 1997, 2000; Kroeger, Swarzenski, Crusius, and others, 2007; Kroeger, Swarzenski, Greenwood, and others, 2007). It is important to note that much of the submarine groundwater is quite young (less than 20 years old) and may represent source areas that are amenable to management.
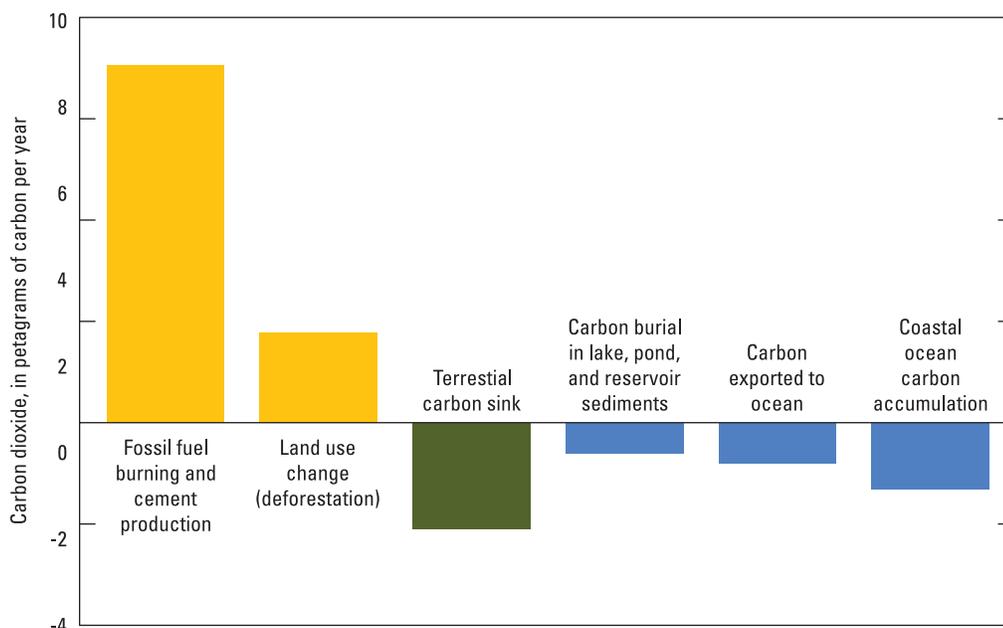

Figure E3. Chart showing the comparison of coastal carbon-sequestration processes to other important sources and sinks. Data from Hedges and Keil (1995), Muller-Karger and others (2005), Dunne and others (2007), Intergovernmental Panel on Climate Change (2007), and Tranvik and others (2009).

Changes in sediment supply also can affect carbon preservation in coastal and estuarine systems. Rivers in the conterminous United States export an estimated 5 to 7 TgC/yr to the oceans in the form of POC (Pacala and others, 2001), some of which is directly preserved through carbon burial (Hedges and others, 1997; Blair and others, 2004). More importantly, however, is the flux of carbon in sediment, which is estimated to be more than 1 PgC/yr (Aulenbach and others, 2007). Sediment supply is a significant control on estuarine and coastal carbon sequestration because the lithogenic minerals in sediments increase the particle floc densities and settling rates, thereby increasing the efficiency of the biological pump (Armstrong and others, 2002). Benthic carbon preservation also is affected because higher rates of burial result in the preservation of a greater fraction of the associated organic material (Boudreau and Ruddick, 1991; Hedges and Keil, 1995; Dagg and others, 2004). Significant changes in the delivery sediment to the coastal oceans have occurred during the past several decades, which has altered the patterns of burial (for example, Vorosmarty and others, 2003; Leithold and others, 2005; Syvitski and others, 2005). Pressures from an increasing population, changes in land use, and changes in patterns of precipitation also will result in changes in sediment discharge (Wilkinson and McElroy, 2007).

Burial of POC—largely derived from phytoplankton—in marine sediments is a major sink in the global carbon budget. Historically, the estimate for the rate of carbon burial in ocean sediments has been approximately 0.15 PgC/yr (Hedges and Keil, 1995; Sarmiento and Gruber, 2002; Muller-Karger and others, 2005). More recent estimates, which explicitly include biogeochemical processes occurring in coastal systems, suggest that this rate may be twice as great (0.32 PgC/yr) (Dunne and others, 2007). Coastal sedimentation accounts for 85 percent of the burial of POC worldwide (Hedges and Keil, 1995; Dunne and others, 2007), with two-thirds of this burial (one-half of the carbon buried in the global oceans) occurring in deltaic sediments of large rivers with high productivity and rapid sediment-accumulation rates (Blair and others, 2004). Much of the remaining burial of carbon in coastal oceans occurs as the result of episodic inputs of sediment from small, mountainous river systems that often occur in tectonically active zones where rates of geologic uplift are high (Milliman and Syvitski, 1992; Blair and others, 2003; Leithold and others, 2005; Wheatcroft and others, 2010); for example, the Eel River in California accounts for 15 percent of the sediment flux from the conterminous United States.

In summary, carbon burial in coastal sediments or its accumulation in the deep ocean is directly related to the riverborne flux of nutrients (which increases coastal primary production) and sediment (which increases the efficiency of benthic burial and the biological pump of carbon into the deep ocean). The coastal carbon-sequestration methodology thus includes a terrestrial-flux component related to land use, a model of coastal primary production that is sensitive to changing nutrient inputs, and a process model that explicitly accounts for controlling processes in carbon remineralization

such as degradation during sinking, ballasting, bioturbation, and burial (Dunne and others, 2005). The modeling approach used here is similar to a sensitivity analysis responding to changes in terrestrial inputs, and thus no seaward boundary is defined; however, because local conditions such as the water-column depth and depositional environment are important elements that control sequestration, the estimates will be conducted individually for large terrestrial inputs, and regionally for smaller ones.

E.4.2. Methane and Nitrous-Oxide Fluxes in Coastal and Estuarine Systems

Changes in production, uptake, and release of methane and nitrous oxide in the sediments of intertidal, estuarine, or coastal waters also can be substantially affected by changes in nutrient fluxes from the terrestrial system (Seitzinger and Nixon; 1985; Seitzinger and Kroeze, 1998) and from groundwater inputs (Bange, 2006; Hirota and others, 2007).

Surface waters of estuaries and coastal waters are typically supersaturated with GHG that are emitted into the atmosphere. The rates of GHG fluxes and their controlling processes, however, are understudied on a national scale, and are likely underestimated. At present (2010), there is insufficient knowledge of CH_4 and N_2O fluxes in estuaries and coastal waters in the United States to either make satisfactory estimates or develop mechanistic models of the fluxes. There is ample evidence, however, that the fluxes are likely to be of substantial size in terms of global warming potential (GWP) relative to carbon and GHG fluxes in other ecosystems, and the fluxes are likely to change in response to human actions, including intentional management to reduce GHG fluxes, and unintended environmental changes that may alter the rates of flux, such as changes in nitrogen loads, sediment-carbon loads, wetland coverage, and the occurrence of hypoxia associated with eutrophication and climate change.

Nitrous oxide.—Because of an increase in nitrogen loading from fertilizer use in watersheds, wastewater disposal, and atmospheric deposition, estuaries are among the most intensely fertilized ecosystems on Earth. Typical fertilizer application rates to turf (about 110 kilograms of nitrogen per hectare per year; Valiela and others, 1997) and to crops (a wide range, but a reasonable average is about 140 kilograms of nitrogen per hectare per year; Valiela and others, 1997) are commonly exceeded by the rates of nitrogen loading to estuaries (for example, Chesapeake Bay main stem, 141 kilograms of nitrogen per hectare per year; Hudson River and Raritan Bay, 900 kilograms of nitrogen per hectare per year; Connecticut River, 3,705 kilograms of nitrogen per hectare per year; Bricker and others, 2007). Because of nearby terrestrial nitrogen sources, global estuarine N_2O fluxes are estimated to be about 7 to 61 percent of total global marine fluxes (Capone, 1991; Bange, 1996; Seitzinger and Kroeze, 1998; Nevison, 2004). At the same time, recent studies suggest that N_2O fluxes from agricultural uses or in soil may be overestimated

(Bange, 2006), in part because consumption of N_2O by the soil has not been appropriately considered (Chapuis-Lardy and others, 2007; Neftel and others, 2007). Thus, values reported by Bange (2006) indicate that estuarine N_2O fluxes may be in the range of 4 to 25 percent of the total global flux from all sources. Furthermore, as argued by Nevison (2000), the Intergovernmental Panel on Climate Change (IPCC) methodology for N_2O fluxes from agriculture has identified measurements of N_2O fluxes from estuaries and from groundwater as critical needs and areas of data collection that need improvement. Recent literature (Nevison, 2000, and references therein) indicates that that the estimates of N_2O fluxes in groundwater that are due to the leaching of nitrogen that results from agricultural practices may need to be revised downward and the estimates of N_2O fluxes in estuaries may need to be revised upward by perhaps 25 percent because of the loss of agricultural nitrogen that is due to leaching.

In addition to fluxes from estuaries, coastal waters outside of estuaries likely contribute significantly to fluxes; furthermore, those fluxes will change in response to changes in anthropogenic nitrogen pollution and possibly to climate change. Part of the nitrogen load on the landscape ultimately transits to continental-shelf waters in discharges from rivers, groundwater, and estuaries, where it fuels denitrification and the production of new organic matter (Sietzinger and Giblin, 1996; Seitzinger and Kroeze, 1998; Seitzinger and others, 2006). The increasing anthropogenic nitrogen and associated new organic matter can be expected to fuel the production of N_2O (Bange, 2006). In an increasing number of locations (fewer than 400 documented worldwide), eutrophication resulting from increasing nitrogen loads is severe enough to produce low-oxygen "dead zones" in estuaries and on continental shelves (Diaz and Rosenberg, 2008), and that process may substantially enhance N_2O fluxes on continental shelves (Naqvi and others, 2000). Bange (2006) compiled published data on N_2O fluxes to the atmosphere from European estuaries and coastal waters and found that much greater flux densities existed within estuaries, but that the larger surface areas of the non-estuary coastal waters contained about 40 percent of the total coastal flux.

Methane.—A global estimate of estuarine CH_4 flux has been attempted (Middelburg and others, 2002). The conclusions, based on a compilation of existing data, suggested that estuaries are consistently a source of CH_4 emissions to the atmosphere and account for about 9 percent of the total global marine source; however, CH_4 fluxes in estuaries are likely to be severely underestimated and are significant to global fluxes (Bange, 2006). Important sources of CH_4 fluxes from estuaries are direct inputs from rivers (Middelburg and others, 2002) and groundwater (Bugna and others, 1996; Crusius and others, 2008; Santos and others, 2009); tidal exchanges with salt marshes, mangroves, and intertidal sand and mud flats (Middelburg and others, 2002; Savvichev and others, 2004; Barnes and others, 2006; Ferron and others, 2007); and production in estuarine sediments (Abril and Iversen, 2002; Kitidis and others, 2007). There are two reasons to conclude that estuarine CH_4 fluxes are underestimated:

- The majority of research attempts to measure dissolved CH_4 concentrations in estuarine surface water focused primarily on the open waters of estuaries, farthest from the nearshore sources listed above, and likely after much of the flux to the atmosphere has already occurred.

- Most of the studies considered in the global flux estimate did not include fluxes from sediments to the atmosphere caused by ebullition of biogenic gas bubbles commonly composed primarily of CH_4.

The neglect of accounting for fluxes caused by ebullitions (bubbles) is likely to dramatically underestimate fluxes because, in the few cases where such fluxes have been measured, they typically included 50 to more than 90 percent of fluxes from sediment (Hammond and others, 1975; Martens and Klump, 1980; Chanton and others, 1989; Hovland, 1993; Shalini and others, 2006; Rajkumar and others, 2008). Further, the importance of ebullitive fluxes is magnified by the fact that such fluxes largely escape oxidation in the sediment and water column (for instance, Martens and Klump (1980) estimated that 85 percent of CH_4 in bubbles survived transit through 7.5 m of water), whereas much of the diffusive flux from sediments is consumed by oxidation before flux to the atmosphere. Fluxes resulting from the release of bubbles are likely to be particularly important in shallow (less than 5 m) waters (Joyce and Jewell, 2003), and their releases are episodic and occur on tidal and seasonal time scales (Chanton and others, 1989), making them difficult to measure and likely to be missed by oceanographic cruises (Hovland, 1993).

Rajkumar and others (2008) provide an example of a study where diffusive and ebullitive fluxes were measured and scaled to an entire estuary. In a 42-km-long, mangrove-fringed estuary with a water-surface area of 690 hectares (ha), ebullitive fluxes accounted for more than 90 percent of the CH_4 flux. In terms of GWP, the CH_4 flux was 453 moles CO_2-equivalents per square meter per year. Comparing this to the rates of carbon sequestration in U.S. forests and non-permafrost peatlands, which are -2.9 and -1.0 moles carbon per square meter per year, respectively (U.S. Climate Change Science Program, 2007), this single estuary has a CH_4 flux equivalent to the GWP of carbon sequestration in about 107,000 ha of forest, or 313,000 ha of peatland.

As discussed with regard to N_2O fluxes in coastal waters, coastal waters outside of estuaries likely contribute significantly to CH_4 fluxes as well. For example, Bange (2006) also compiled published data on CH_4 fluxes from European estuaries and coastal waters, and similarly found much higher flux densities within estuaries. Still, fluxes from non-estuarine coastal waters once again were responsible for about 40 percent of the total coastal flux.

Potential for change.—GHG fluxes from estuaries and coasts are likely evolving in response to environmental changes and human actions, including changes in nitrogen and phosphorus loading; inputs of GHG from rivers, groundwater,

and wetlands; delivery of sediment; wetland coverage because of removal, restoration, or sea-level rise; and sediment loading because of dredging. Climate change can be expected to alter estuarine and coastal GHG fluxes in as yet unquantified ways because of sea-level rise and temperature increases. In recent decades, the areal coverage and intensity of coastal dead zones (hypoxic and anoxic zones) has increased dramatically in the United States and worldwide because of increasing nutrient loading (Diaz and Rosenburg, 2008), and climate change is expected to exacerbate that process (Justic and others, 2003; Boesch and others, 2007). Both eutrophication and associated increases in OC production and low dissolved oxygen conditions are likely to increase CH_4 production (Giani and Ahrensfeld, 2002) and decrease CH_4 oxidation (consumption) in estuaries. N_2O fluxes are expected to increase in response to increasing nitrogen supply: Seitzinger and Kroeze (1998) suggest that the proportion of the nitrogen released to aquatic environments that is converted to atmospheric N_2O depends on the nitrogen loading rate—from about 0.3 percent under conditions of low nitrogen loading, to 3 to 6 percent with higher nitrogen loading. Hypoxic and anoxic zones may be particularly important sources of N_2O (Naqvi and others, 2000). Because CH_4 fluxes from some estuaries and coasts may be large, and the assessment is focused on changes during the next four decades, it is worth noting that, over a 20-year period, the GWP of CH_4 is estimated at 72 CO_2 equivalents rather than the 25 CO_2 equivalents typically considered over a 100-year period (Intergovernmental Panel on Climate Change, 2007).

Coastal groundwater as a source.—GHG fluxes from coastal groundwater also have received little attention, but data do exist and indicate that concentrations of N_2O and CH_4 are at times quite elevated in coastal groundwater (Butler and others, 1987; LaMontagne and others, 2003; Santos and others, 2009). Further, the global inventory of N_2O in groundwater is a large, accounting for perhaps 10 to 20 percent of all biogenic N_2O (Ronen and others, 1988; Haag and Kaupenjohann, 2001). Correlations between radon activity (which acts as a tracer of groundwater discharge) and concentrations of dissolved CH_4 (Bugna and others, 1996; Santos and others, 2009) and N_2O (Crusius and others, 2008) suggest that groundwater is a dominant source for those dissolved gases in some estuaries. Finally, coastal groundwater may interact in important ways with CH_4 production in estuarine sediments. Several authors have noted associations between the presence of discharging fresh groundwater in pore waters and elevated CH_4 concentrations in shallow sediments, which suggests either (1) the reduced sulfate inhibition of methanogenesis in low-salinity water or (2) in some cases, the delivery to the estuary of terrestrial groundwater that is enriched in dissolved methane, which is the result of onshore aquifer properties and the influence of freshwater wetlands and hydric soils (Hill and others, 1992; Bratton and others, 2004; Kogan and Paull, 2005). The assessment will, therefore, explicitly consider groundwater as a source for coastal GHG.

E.4.3. Methodology for Assessing and Projecting Carbon Sequestration and Greenhouse-Gas Fluxes From Coastal and Estuarine Systems

There are three subsections to the coastal and estuarine assessment methodology. The first subsection describes the methods used to assess the terrestrial supply of dissolved and particulate organic carbon, nutrients, and sediments to the coastal oceans. The second subsection describes the methods used to assess the role of estuaries and coastal processes in carbon storage. The third subsection describes a method for estimating the GHG fluxes from coastal and estuarine waters, intertidal sediments, and tidal systems not covered in the wetland assessment.

Wetlands restoration or destruction and other changes caused by sea-level rise will substantially affect carbon storage, carbon sequestration, and GHG production along coastal margins in the terrestrial to aquatic transition zone. Because the methods used to assess wetlands and sea-level rise are contained within the models used to assess terrestrial processes (as discussed in appendixes C and D in this report), these methods are not described here. Nevertheless, the effects of changes to coastal and estuarine wetlands and changes because of sea-level rise are represented in the coastal and estuarine methodology because those changes affect nutrient, carbon, and sediment fluxes.

The goal of the coastal and estuarine assessment is to assess the magnitude of linkages between terrestrial land use, coastal carbon sequestration, and GHG production, as driven by changes in the flux of water, nutrients, sediment, and carbon from the continent. The coastal and estuarine assessment focuses exclusively on the carbon-sequestration and GHG-production functions of estuaries and coastal systems that are presently (2010) affected or may be affected by changes in terrestrial processes in response to changing management, land use, population, or climate. Given that the modeled processes differ because of variations in coastal geomorphology and continental flux, the assessment will be segmented into physiographic regions, but the seaward spatial boundary will remain undefined.

The methodology for assessing and projecting carbon sequestration and GHG fluxes for coastal and estuarine systems has four parts: (1) surface-water fluxes of carbon, nutrients and sediments to estuaries and coasts; (2) groundwater fluxes to estuaries and coasts; (3) carbon preservation in coastal waters; and, (4) release or uptake of methane and nitrous oxide.

E.4.3.1. Surface-Water Fluxes of Carbon, Nutrients, and Sediments

The methods used to assess the carbon sequestration and GHG productions in coastal and estuarine systems require the determination of the terrestrial fluxes that affect these processes. Current (2010) fluxes and future potential fluxes under different climate and land-use scenarios will be assessed

using a hybrid modeling approach (the SPARROW model) that combines process-based and statistical models to calculate constituent fluxes from rivers (head of tide) to estuaries and the coastal zone across the United States. The datasets that drive the SPARROW model will include the LULC data generated as part of the assessment effort (described in chapter 3 and appendix B of this report). Modeled data will be produced for all coastal and inland hydrologic units that produce runoff to estuaries in the United States and will be developed for DOC, POC, total suspended sediments (TSS), nitrogen (organic and inorganic) and phosphorus (organic and inorganic). The assessment also will incorporate estimates of the submarine groundwater flux to estuaries from coastal basins using values derived either from the existing literature or from models. This broader methodology will not consider inorganic carbon (dissolved CO_2 or particulate) or micronutrients (silica, iron) at this time.

The goals of this part of the assessment are (1) to estimate the mean annual flux of POC, TSS, and nutrients from hydrologic basins across the United States to the head of tide; (2) estimate the mean annual flux of particulate carbon, TSS, and nutrients from coastal landscapes below the head of tide; and (3) develop new SPARROW models for key constituents that affect coastal carbon cycling, including organic nutrients, POC, and carbon degradation. The lateral-flux estimates described earlier will be conducted in coordination with these assessments.

A variety of modeling approaches have been used to estimate constituent contaminant sources and loads in basins including process-based and statistical models with a range of complexities (Alexander, Elliot, and others, 2002; Schwarz and others, 2006). Process-based (mechanistic) models, such as the Hydrological Simulation Program-Fortran (HSPF) (Bicknell and others, 2001) and the Soil and Water Assessment Tool (SWAT) (Srinivasan and others, 1993), use a detailed set of equations that attempt to describe relevant processes affecting water and constituent transport. These models typically have a complex mass-balance structure that requires a large number of input parameters and assumptions about the dominant processes and reactions rates (Schwarz and others, 2006). In addition, these models often lack robust measures of uncertainty in model coefficients and predictions and suffer from challenges in extrapolating the results of small catchment models and field-scale measurements to larger spatial scales; however, these models are based on physical processes occurring in basins and drainage networks and theoretically would be applicable across a broad range of sites with detailed input data.

In comparison, statistical models have a simple correlative mathematical structure and use empirical relations, such as linear regression between stream measurements (load, concentration) and sources or landscape drivers. Examples of purely statistical models include regressions of nitrogen export from large basins on population density (Peierls and others, 1991), net anthropogenic sources (Howarth and others, 1996), and atmospheric deposition (Howarth and others, 1996;

Jaworski and others, 1997). Although these models can be applied in basins of various sizes and can incorporate uncertainty estimates, they typically use a "black box" approach that lacks a mechanistic explanation of the processes affecting contaminant transport (Schwartz and others, 2006). In addition, these models also lack spatial details about the distribution of sources and sinks within basins and do not allow for an assessment of the relative importance of terrestrial versus aquatic processes.

Hybrid modeling approaches (SPARROW, Smith and others, 1997; Global NEWS, Seitzinger and others, 2005; PolFlow, de Wit, 2001) expand on simple statistical models by adding process-based model structures to develop relations with spatially referenced properties. For example, SPARROW has process-based mass-transport components for water-flow paths, in-stream processing, and mass-balance constraints on model inputs, losses, and outputs (Schwarz and others, 2006). Parameters are estimated for monitoring stations that have sufficient records for discharge and water-quality measurements (including capturing the dynamic range) by spatially correlating stream data with georeferenced data that describes constituent sources (atmospheric deposition, fertilizers, human and animal wastes) and delivery factors (precipitation, topography, vegetation, soils, water routing). Parameter estimation ensures that the calibrated model will not be more complex than can be supported by the data.

SPARROW has been included in several model comparison studies with process-based and statistical models. These include comparisons of total nitrogen (TN) loading with the models at the national scale and for the Chesapeake Bay Basin (Alexander and others, 2001). Alexander, Johnes, and others (2002) and Seitzinger and others (2002) also compared statistical and hybrid models for the northeastern United States, with results typically showing a general agreement between the models and the literature estimates, but lower estimates of uncertainty with SPARROW when it was compared to many other models (Alexander, Johnes, and others, 2002).

In this part of the assessment, SPARROW will be used to model the delivery of terrestrial carbon and other constituents in rivers to the coastal zone. Understanding carbon transport requires models that cover the conterminous United States and that estimate the loading of key constituents to estuaries and coastal systems. A number of previous studies have used the SPARROW model for national-scale assessments of TN and total phosphorus (TP) sources and loads throughout the conterminous United States (Alexander and others, 2001; Smith and others, 2003). Separate regional studies of TN and TP loads also have been conducted in the Chesapeake Bay Basin (Preston and Brakebill, 1999; Brakebill and Preston, 2003; Roberts and Prince, 2010), the Mississippi River and tributaries (Alexander and others, 2008; Robertson and others, 2009), and New England (Moore and others, 2004). Although most studies to date have focused on TN and TP, SPARROW models also have also been developed for a range of parameters including *Escherichia coli* (*E. coli*) (Puri and others, 2009), suspended sediment (Schwarz and others, 2006), and national

estimates of total organic carbon, and dissolved solids (Anning and others, 2007).

SPARROW model parameters are estimated using nonlinear regression techniques by spatially correlating constituent flux estimates at monitoring stations with geospatial data about constituent sources and factors affecting constituent fate and transport. The calibrated models are used to predict flux and to estimate the source contributions for stream reaches throughout a river network (Schwarz and others, 2006). Data for in-stream nutrient loads at monitoring sites, nutrient sources, and land-surface characteristics are assigned to each stream reach in a digital stream-reach network, which provides continuity between upstream and downstream loads. The model uses mean annual loads typically from a large number of sites according to site-selection criteria, including the minimum number of observations at each station, a maximum prediction accuracy of plus or minus 50 percent of the mean annual load, and sufficient coverage of basin-attribute data (Schwarz and others, 2006; Alexander and others, 2008). Statistical approaches such as LOADEST (Runkel and others, 2004) and Fluxmaster (Schwarz and others, 2006) then are used to develop a time-series flow model and estimate the water-quality model (Schwarz and others, 2006).

The SPARROW model relates water-quality and streamflow measurements to spatially referenced characteristics of watersheds as described in Schwarz and others (2006). The stream reach (and its incremental contributing drainage basin) is the basic spatial unit that is used in the SPARROW models. Data collected at different spatial scales (for example, by census block or county) are converted to the stream-reach scale using GIS techniques (Schwarz and others, 2006).

To accomplish this assessment, the monitoring and geospatial data will be collected and evaluated for use in SPARROW models of constituent transport to the head of tide. Potential data sources are included in tables 3.7 and 3.10 in this report. The assessment will (1) use land-use and land-cover data that is generated from the "forecasting scenarios of future land-cover" (FORE–SCE) model (described in appendix B of this report) to project to 2050 at 250-m grid-cell resolution; and (2) evaluate existing data, test assumptions, and develop correlations between parameters such as fertilizer-application rates and atmospheric deposition over time. The assessment also will include uncertainty estimates for parameters that have significant assumptions associated with them or are difficult to evaluate. Given that most SPARROW models are developed for studies of TN and TP, additional data types or sources may be required for models of other constituents that affect the terrestrial-carbon contributions to estuaries and coastal systems.

The SPARROW model's output contains prediction results paired with measures of accuracy in stream reaches. Constituent transport is predicted as fluxes (mass over time) at both the reach and incremental basin scales, and statistical analyses are performed on the prediction results (standard errors, prediction intervals). Fluxes then are used to derive constituent yields (mass over area over time), flow-weighted

concentrations (mass over volume), and contributions by source (Schwarz and others, 2006). The SPARROW model provides estimates of the long-term mean annual or mean season flux (mass per unit time) of various constituents

In the assessment, the transport of constituents to the head of tide will focus on an annual time scale and will be referenced to a specific year as described in Schwarz and others (2006); however, the development of parameter-estimation methods for applying the SPARROW model at shorter time steps (for example, seasonal or monthly; Schwarz and others, 2006) will be evaluated early in the study using existing TN and TP in order to develop a more mechanistic understanding of processes, fluxes, and temporal variability that will inform future model development and interpretation of the annual-scale results. A number of terrestrially derived constituents affect carbon cycling in estuaries, and therefore need to be included in model output. Critical constituents currently (2010) modeled by SPARROW or that are in development include DOC, TSS, TN, and TP. The current (2010) methodology also will use SPARROW modeling to predict the form of dissolved nitrogen (inorganic versus organic) and POC transport because both are critical to carbon cycling in estuaries and coastal systems.

E.4.3.2. Groundwater Fluxes of Carbon and Nutrients

The SPARROW model and streamgage data do not estimate groundwater fluxes of carbon and nutrients to coastal waters. To adequately estimate these loads, the assessment must explicitly estimate and model groundwater loads using a land use and geological typology approach. Nitrogen loads to estuaries and coasts from groundwater discharge will be estimated using existing information about discharges and loads, and a typological approach will scale the site-specific rates to larger sections of the United States coast. A number of published USGS reports include estimates of groundwater discharge rates from specific basins that are based on hydrological modeling, commonly using various versions of the USGS's groundwater-flow model (MODFLOW) or related groundwater models (U.S. Geological Survey, 2010c); for example, see Scorca and Monti (2001) for the north shore of Long Island; Monti and Scorca (2003) for the south shore of Long Island; Sanford and others (2008) for the Chesapeake Bay; and Masterson and others (2006) for Rhode Island. The groundwater-discharge estimate from those studies will be applied, as a proportion of total rainfall to the catchment, to neighboring locations of similar climate and geology. Where available, results will be compared to estimates of groundwater discharge at particular locations that have been published in journal articles. The concentrations of nitrogen, carbon, and GHGs in discharging groundwater will be estimated on the basis of published data about selected sites on the east coast of the United States, including Kroeger and others (1999), Bratton and others (2004, 2009), Crusius and others (2005), Cole and others (2006), Kroeger, Cole, and Valiela (2006), Kroeger, Cole, York, and Valiela (2006), Kroeger, Swarzenski,

Crusius, and others (2007), Swarzenski and others (2007), and Kroeger and Charette (2008); and USGS monitoring data for several thousand wells, which are available through the USGS's National Water Information System (NWIS). The NWIS data will be selected based on well depth and proximity to the coast. The suitability of the data for indicating concentrations of carbon and nutrients in discharging groundwater will be assessed by comparing the NWIS data to other USGS data. Nitrogen concentrations and loads in groundwater will be further estimated based on the application of a modified version of Nitrogen Loading Model (NLM) (Valiela and others, 1997, 2000). NLM is an empirical, land-use-based model of groundwater nitrogen loads to estuaries. The model will be applied to the nearshore parts of basins that are not accounted for in SPARROW.

E.4.3.3. Carbon Preservation in Coastal Systems

The assessment of carbon preservation in coastal systems also will use a hybrid modeling approach and will be conducted in two tiers. The goals of this part of the assessment are (1) to quantify the mean annual flux of carbon into the sediments in coastal and estuarine environments, where it is buried; (2) to estimate the mean annual net flux of terrestrially supported, phytoplankton-derived, "new" carbon production into the sediments, across the thermocline, and into the deep ocean; and (3) to develop a new modeling structure for coastal carbon cycling that incorporates variations in terrestrial inputs, POC degradation, burial, and transport to the deep ocean.

The conceptual modeling structure for this effort (fig. E4) begins by measuring the effects of changing nutrient fluxes from terrestrial systems on productivity (and hypoxia) in coastal waters. Inputs of POC from sediments in the rivers will contribute to the flux of carbon to the coastal sediments, but will

also act to ballast algal production, which will increase transport through the mixed layer. Depending on the water depth and local currents, the particles are transported to the sediment surface or to a layer below the thermocline, where the carbon is essentially sequestered (Hales and others, 2006). Particles arriving at the sediment surface are subject to continued degradation and resuspension until they are buried deeply enough so that penetration of oxygen into the sediment is not possible and therefore where the carbon is presumed to be sequestered (Hedges and Keil, 1995; Hartnett and others, 1998).

The first major process to be modeled is carbon accumulation in coastal sediments, which, as discussed above, is a function of coastal productivity and sediment-accumulation rate. The vast majority of carbon preserved in the ocean is derived from marine sources and occurs in coastal sediments, mainly in deltas (Hedges and Keil, 1995). The initial assessment of carbon sequestration occurring in these systems will be based on the sediment-flux values provided by the methods described in section E.2 ("Transport of Carbon by Streams and Rivers") of this report, using values for carbon contents provided in Hedges and Keil (1995) and other relevant publications that contain data on carbon content and grain-size distribution in major deltas of the United States. The previously published estimates of carbon accumulation are based on an assumed partitioning between deltaic and coastal sediments, and the carbon contents are reported separately for each of the two environments.

The same assumptions that are presented in Hedges and Keil (1995) initially will be used until a diffusional model is implemented in conjunction with a sedimentation model (discussed below). It is anticipated that under some IPCC SRES scenarios (Nakicenovic and others, 2000), ocean warming will increase stratification of the sediments and induce additional
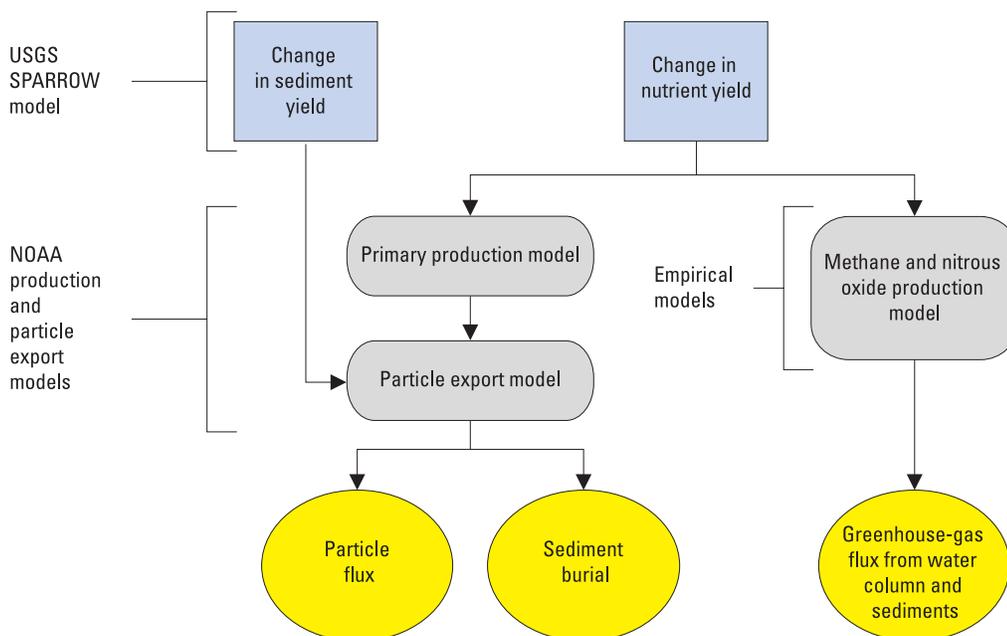

Figure E4. Diagram showing the modeling structure for coastal carbon-sequestration processes. Acronyms are as follows: NOAA, National Oceanic and Atmospheric Administration; SPARROW, "spatially referenced regression on watershed attributes" model; USGS, U.S. Geological Survey.

hypoxia (Levin and others, 2009). Our estimates will be adjusted based on the anticipated extent of hypoxic areas in many major river deltas (Howarth, 2008; Rabouille and others, 2008), whereby sediments underlying these suboxic zones will exhibit elevated levels of carbon preservation because of matrix protection and reduced microbial activity (Bergamaschi and others, 1997).

The second process to be modeled is the flux of the phytoplankton biomass across the thermocline, which is based on models developed by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (Dunne and others, 2005) and conducted in collaboration with the NOAA team. They have developed a combined statistical-mechanistic model using global data that estimates the phytoplankton's size distribution, water temperature, and a variety of other ecosystem variables. Ballasting, sinking rate, remineralization rate, and other relevant mechanistic variables also are included to assess the export of carbon from the photic zone. The model will be adapted for estimating the flux of phytoplankton biomass in coastal areas and for determining carbon flux to the sediments in shallow zones and below the thermocline in deeper zones.

This modeling approach divides the processes into productivity based on sediment preservation and productivity from the biological pump. The first model component assesses the amount of coastal productivity supported by nutrient supply from rivers. Changes in nutrient supply can be caused by changes in population, discharge, agricultural practice, reforestation, and many other similar land-use- or climate-related variables (Billen and Garnier, 2007) and will affect the primary productivity in adjacent coastal areas.

At present (2010), the assessment will calculate nutrient loads and sediment and POC flux rates to coastal segments at monthly time increments. A discharge intensity factor will be used to assess dispersion, and an energetic factor to assess resuspension cycles—estimated as a function of bathymetry and wind energy—that affect the processing of organic carbon associated with particles (Burdige, 2005; Thunell and others, 2007). Resuspension of particles that results from large events such as hurricanes (Chen and others, 2009) is not taken into account.

The model will use monthly time increments to incorporate seasonal as well as temporal changes in the river-ocean interface, which can have a large effect on the fate of POC in coastal ocean systems (Wheatcroft and others, 2010). Dunne and others (2005, 2007) include a complete model description, model parameters, and equations. Data needs and sources are listed in table E1.

E.4.3.4. Net Production of Methane and Nitrous Oxide in Estuaries and Coastal Waters

Fluxes of N_2O and CH_4 from estuaries and coastal waters will be assessed based on empirical data about flux rates and will involve a geospatial approach to quantify the coverage of key sources including salt marshes, mangroves, and intertidal areas. Where data are available, a regression approach will be used to estimate flux rates based on spatial or temporal variations in controlling variables. In cases where insufficient data are available for a simple regression approach, information gaps initially will be filled with estimated unit values. For example, all fringing salt marshes initially will be estimated to contribute CH_4 to adjacent estuaries at the same (albeit poorly constrained) rate.

Terrestrial inputs of N_2O and CH_4 will be estimated through linkages to measured and modeled discharges and chemical compositions of rivers and groundwater. Methanogenic aquifers will be identified on the basis of proposed geological controls. The N_2O and CH_4 content of coastal groundwater and rivers will be estimated based on LULC regressions (appendix B of this report), geological setting, biogeochemical conditions, chemical data synthesized from published literature, USGS monitoring data for groundwater and rivers available through NWIS, and other data sources, as available. Future changes in terrestrial N_2O fluxes will be estimated based on modeled changes in nitrogen loads (SPARROW; NLM; Valiela and others, 1997, 2000), projected land-use changes, and an assumed proportion exported as N_2O (for example, Seitzinger and Kroeze, 1998). Where data are available, the variables to be considered will include eutrophication status, nitrogen load, hypoxia and anoxia, wetland coverage and type, latitude, climate, terrestrial-sediment load, carbon content of the sediment, water depth, salinity, and temperature or season. Given the limited data availability on N_2O and CH_4 in rivers and groundwater, the assessment will require limited new data collections and monitoring to fill knowledge and data gaps, and will require uncertainty estimates.

The N_2O flux to the atmosphere from the water column will be calculated as the sum of nitrification and denitrification rates multiplied by the emission factor (EF), which is the proportion of the production rate of N_2O versus other products (nitrate or N_2) in those transformation processes (Seitzinger and Nixon, 1985; Seitzinger and Kroeze, 1998). The EF is calculated based on experiments showing that N_2O / N_2 as a product of sediment denitrification increased linearly with nitrogen load ($r^2 = 0.97$) and the EF for nitrification has been observed to vary from 0.3 to 30 percent (Goreau and others, 1980; Priscu and others, 1996). Thus, in the methodology, the EF will be calculated as a fraction of the total N transformation by denitrification and nitrification, and that fraction will increase with the N load per unit area of estuary. The denitrification rate is assumed to be 50 percent of the nitrogen-loading rate, supported by a regression between those variables ($r^2 = 0.81$ versus inorganic nitrogen load; $r^2 = 0.7$ versus total nitrogen load) (Seitzinger and Kroeze, 1998). The modeled pelagic nitrification rate is less constrained and is assumed to be 1.2 times the denitrification rate, which is based on observations in Narragansett Bay (Seitzinger and others, 1984). Benthic nitrification is not included, although the rate has been observed to be approximately equivalent to pelagic nitrification (Berounski and Nixon, 1993). For the methodology, the total dissolved nitrogen (TDN) loads will be estimated

Table E1.   Examples of data requirements and sources for coastal and estuarine assessment.

[Partial list. Final sources will be selected in consultation with stakeholders and assessment team members. Abbreviations and acronyms are as follows: DEM, digital elevation model; DOC, dissolved organic carbon; GIS, geographic information system; km, kilometer; lbs/yr, pounds per year; LOADEST, Load Estimate; LULC, land use and land cover; m, meter; N, nitrogen; NADP, National Atmospheric Deposition Program; NCDC, National Climatic Data Center; NED, National Elevation Dataset; NHD, National Hydrography Dataset; NOAA, National Oceanic and Atmospheric Administration; NPCDI, National Coastal Pollutant Discharge Inventory; NPDES, National Pollutant Discharge Elimination System; NWIS, National Water Information System; POC, particulate organic carbon; ppt, parts per trillion; PRISM, "parameter-elevation regressions on independent slopes" model; SSURGO, Soil Survey Geographic Database; STATSGO, U.S. General Soil Map; STORET, Storage and Retrieval Data Warehouse; USDA, U.S. Department of Agriculture]

Type	File	Description	Source
Atmospheric nitrogen deposition			Wet deposition of nitrate-N from NADP (http://nadp.sws.uiuc.edu/).
Bathymetry	GIS	NOAA estuary bathymetry maps—includes 30-m DEM, Google Earth files, detailed metadata, images (soundings and nautical charts), estuary-footprint shape files, images	http://estuarinebathymetry.noaa.gov/finddata.html. http://coastalgeospatial.noaa.gov/data_gis.html.
Calculated constituent loads	Site specific		Data: NWIS (http://waterdata.usgs.gov/nwis), STORET (http://www.epa.gov/storet/), other sources. Calculations: LOADEST, Runkel and others, 2004 (http://water.usgs.gov/software/loadest/). Fluxmaster, Schwarz and others, 2006.
Climate (precipitation, air temperature)			PRISM (http://www.prism.oregonstate.edu/index.phtml). NCDC (http://lwf.ncdc.noaa.gov/oa/ncdc.html). Daymet (http://www.daymet.org/.
Coastal primary productivity	GIS	Primary productivity calculated from satellite chlorophyll data	http://www.csc.noaa.gov/digitalcoast/data/index.html.
Fertilizer use			Ruddy and others, 2006 (http://pubs.usgs.gov/sir/2006/5012/). http://coastalgeospatial.noaa.gov/data_table.html.
Population density			Provided by LULC modeling team. Derived 200-m U.S. Census Bureau datasets from 1990 and 2000 (http://www.census.gov/).
In-stream and water-column losses		First-order decay functions	Schwarz and others, 2006; Dunne and others, 2007; other primary literature sources.
Land use	GIS		Provided by LULC modeling team.
National estuarine eutrophication assessment	Website	Data on individual watersheds from other datasets	http://ian.umces.edu/neea/.
Nutrient, POC, DOC concentrations in rivers	Site specific		http://waterdata.usgs.gov/nwis.
Permitted waste discharges			NPDES (http://www.epa-echo.gov/echo/compliance_report_water_icp.html).
Physical and hydrologic characteristics	Data tables	Watershed areas (including land versus water), mean streamflow, mean monthly streamflow, tidal information	http://coastalgeospatial.noaa.gov/data_table.html.
Physical features	GIS	NOAA GIS maps of shorelines, rivers, lakes, LULC by (1) coastal (estuarine) watershed, (2) upstream (fluvial) watersheds, (3) interior watersheds	http://coastalgeospatial.noaa.gov/data_gis.html. http://www.csc.noaa.gov/digitalcoast/data/ccapregional/.
Pollution sources	Tables	Data on non-point and point source loading (lbs/yr) for a wide range of nutrients and metals, as well as by land use and upstream sources	NPCDI; http://coastalgeospatial.noaa.gov/data_table.html.
Salinity zones	GIS	NOAA GIS data with average annual salinity zones by region—mixing zone (5–25 ppt), seawater zone (25 ppt), tidal fresh zone (0–5 ppt)	http://coastalgeospatial.noaa.gov/data_gis.html.
Soils (permeability, porosity)			1-km resolution data on soil permeability and porosity from USDA STATSGO and SSURGO database. STATSGO (http://soils.usda.gov/survey/geography/statsgo/). SSURGO (http://soils.usda.gov/survey/geography/ssurgo/).
Stream reaches	GIS		Enhanced River Reach File (ERF1) (Alexander and others, 1999) (http://water.usgs.gov/lookup/getspatial?erf1). NHD, http://nhd.usgs.gov/index.html. NED, http://gisdata.usgs.net/ned/.
Topography	GIS		Nolan and others, 2002 (http://water.usgs.gov/GIS/metadata/usgswrd/XML/erf1_2.xml).
Topography (slope, topographic indices)			Nolan and others, 2002 (http://water.usgs.gov/GIS/metadata/usgswrd/XML/erf1_2.xml).
Watershed boundary	GIS		Watershed Boundary Dataset (http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/).
Temperature		Satellite-based surface	http://coastalgeospatial.noaa.gov/data_gis.html.
Wind speed and direction			http://coastalgeospatial.noaa.gov/data_gis.html.

on the basis of the sum of the loads from rivers (derived from the SPARROW model), direct groundwater discharge (derived from the NLM groundwater nitrogen model), and atmospheric deposition (derived from National Atmospheric Deposition Program (NADP) data). Modeled N_2O flux rates from estuaries will be calculated as follows:

$$N_2O = EF \times (NIT + DENIT) \qquad (E4)$$

calculated as $NIT = 1.2 \times DENIT$
$DENIT = 0.5 \times TDNinput$
$N_2O = EF \times 1.1 \times TDNinput$

where N_2O is the N_2O flux (in grams of nitrogen per year)

         EF   is the emission factor and equals N_2O/N_2 or $(1.12 \times 10^{-7}) \times$ kilograms of nitrogen per square kilometer of estuary per year

         NIT   is the pelagic nitrification rate (in grams of nitrogen per year)

         DENIT   is the sediment denitrification rate (in grams of nitrogen per year)

         TDNinput   is the external total dissolved nitrogen load from rivers plus groundwater plus atmospheric deposition (in grams of nitrogen per year)

This simple empirical model is intended to produce coarse estimates of fluxes because the availability of data to construct and validate the model is extremely limited; therefore, the model will be updated continuously as additional validation data become available. Field research and monitoring will be required to further develop, test, validate, and calibrate the model.

E.4.4. Validation and Error Estimation

Bootstrap methods will be used in the SPARROW model to address uncertainties in parameters and correct for potential bias (Schwarz and others, 2006; Robertson and others, 2009). The output from SPARROW provides statistics that can be used to evaluate the results, such as an analysis of spatial bias and measures of model fit (Schwartz and others, 2006). Monte Carlo methods will be used to estimate uncertainty in models of coastal productivity and carbon accumulation (Dunne and others, 2005). Models will be validated using continuous monitoring data such as that produced by the USGS National Stream Quality Accounting Network (NASQAN) and other programs. Parameter data will be validated by comparing it to existing scientific literature. Modeled accumulation rates will be validated using existing and proposed core data.

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[Reports that are only available online may require a subscription for access.]

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Appendix F. Methods for Analyzing Ecosystem Services and Benefits and Costs of Mitigation Activities

The assessment results will be important to a broad range of users to help quantify potential effects and effectiveness of mitigation strategies (land-use and land-cover change, land-management activities), ancillary effects on ecosystem services, and associated economic and social costs for carbon sequestration and reduction of greenhouse-gas emissions. This appendix includes additional material on quantifying ecosystem services and estimating the present value of the benefits of those services and the costs of a management activity.

F.1. Ecosystem Services

Quantifying and projecting changes in carbon stocks and greenhouse-gas (GHG) emissions resulting from climate change, management actions, and mitigation strategies will be based on the accounting approach (using a spreadsheet) and the process-based probability approach (using the General Ensemble Modeling System (GEMS)) as described in section 3.3.4 and appendix D of this report. Many of these primary assessment data products also can be categorized as ecosystem services, including carbon stocks in soils and vegetation, carbon sequestration, methane and nitrous-oxide emissions, net ecosystem production (NEP), timber production, grain production, and soil erosion. Estimates of value for these ecoregion services can be produced for each ecoregion reporting unit because they will be based on the primary assessment data products.

For other services not produced within the GEMS biogeochemical models or spreadsheets, the assessment will use an integrated ecosystem modeling approach (Starfield and Chapin, 1996) to quantify the ancillary effects of management activities and mitigation strategies on important ecosystem services. This approach builds on the state-transition model concept by linking conceptual, statistical, and mechanistic models in a spatially explicit framework. The modeling and data components contained within the framework of the integrated ecosystem services model use "forcasting scenarios of land cover change" (FORE–SCE) outputs as the initial basis for the spatial distribution of land use and land cover (LULC) in a given landscape. Biophysical production functions are constructed from known relations between the LULC class ecosystem attributes and the relevant ecosystem services (Nelson and others, 2008, 2009). For wildlife habitat, habitat-suitability index methods will be used wherein the composition and structure at the site and landscape scales control the amount and quality of suitable habitat for a given species or guild (Wakely and Roberts, 1996; Villard and others, 1998; Tirpak and others, 2009). Because forest-stand composition and structure correlate with habitat suitability, growth and

yield models such as the Forest Vegetation Simulator (FVS) (Crookston and Dixon 2005, Chivoiu and others, 2006) and the Forest Landscape Disturbance and Succession Model (LANDIS–II) model (He and others, 2005) are two of the models that may be used. Site-occupancy modeling (MacKenzie and others, 2006) accounts for variation in detection probability and produces robust estimates of the proportion of area occupied (PAO) for specific species. For a service like waterfowl habitat, values can be computed as a function of the energy values of different crops (mapped according to U.S. Department of Agriculture's (USDA) National Agricultural Statistical Service (NASS) program) and vegetation types and converted into duck energy days (DEDs, the amount of energy required by one mallard-size duck for one day) (Kross and others, 2006).

Other services, such as sediment and nutrient retention, require data on relevant driver-stressor relations, which can be derived from current research, primary scientific literature, and expert workshops. The widely used Soil and Water Assessment Tool (SWAT) can be used to estimate the land-phase processes (for example, surface runoff, soil erosion, nonpoint-source nutrient loss, groundwater recharge, and base flow) and water-phase processes (for example, water routing, sediment transport, and nutrient transport and its fate in the aquatic systems). GEMS will link with SWAT to assess the climate-change effects on water availability, and sediment and nutrient transport over landscape.

A distributed geospatial-model-sharing platform will be used to model ecosystem services and provide decision support (fig. F1). This platform is necessary to facilitate sharing and integrating geospatial disciplinary models. A platform based on Java Platform Enterprise Edition (J2EE) and open-source geospatial libraries (Feng and others, 2009) is in development. Shared models on the platform can be accessible to applications through the Internet using the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard (fig. F2). A pilot platform, EcoServ, was developed in the Prairie Pothole Region (PPR) to simulate diverse ecosystem services simultaneously at the landscape scale.

Given the need to have regionally specific information and the limited understanding of the complex relations among ecosystem processes, management actions, climate change, and ecosystem services, this part of the assessment will be limited to case studies within selected ecoregional assessment units where data and models have been developed and can be readily incorporated into the assessment framework. Likely areas include the Mississippi Alluvial
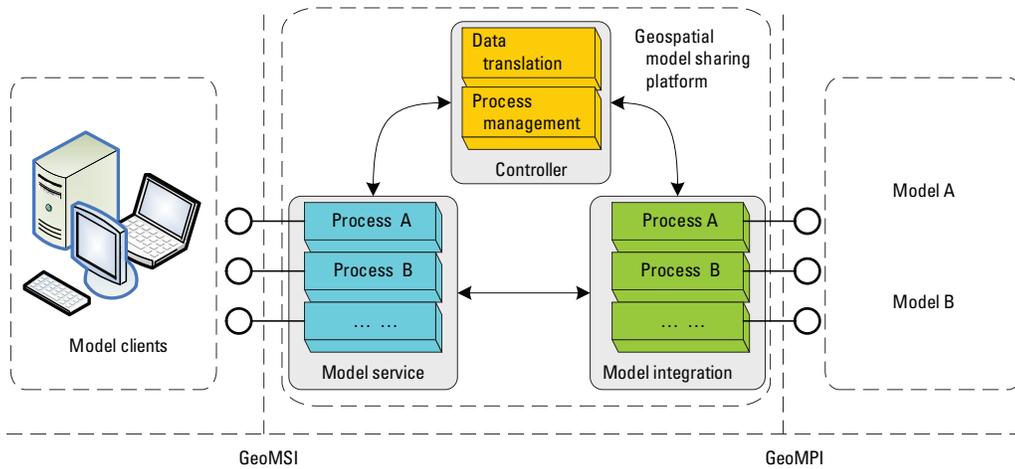
Figure F1. Diagram showing the system structure of the geospatial-model-sharing platform. GeoMSI, geospatial model service interface; GeoMPI, geospatial model processing interface. Modified from Feng and others (2009), used with permission.
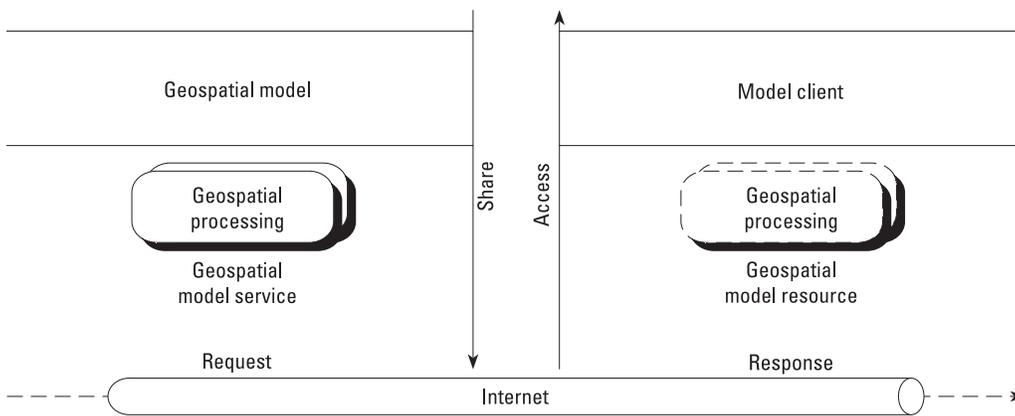

Figure F2. Conceptual flow diagram of accessing shared geospatial model. Modified from Feng and others (2009), used with permission.

Valley, Prairie Pothole Region, southern Florida, and the Chesapeake Bay Basin.

F.2. Costs and Benefits

The present value of the benefits (PVB) of a management activity are entered into the formula for calculating the present value of benefits in equation F1. Carbon sequestration is assumed to start accruing in the 10th year of the activity. All other benefits begin in year 1 of the activity or 1 year after the initial investment in establishing the activity.

$$PVB = \sum_{t=1}^{T} \frac{B_t}{(1+r)^t},$$ (F1)

where t is time,
          T is the terminal year for the mitigation activity,
          r is a discount rate, and
          B is the gross ecosystem service benefits associated with a management activity.

Present value cost (PVC, equation F2) of management activities is the discounted sum of land value, variable costs of production (McKenney and others, 2004), and the equivalent annual cost (EAC, equation F3) values for the time horizon of the analysis (Stavins and Richards, 2005). Estimation of the PVC and EAC use the following equations. PVC in equation F2 represents the formulation of the present value of the economic costs of a sequestration mitigation activity:

$$PVC = \sum_{t=0}^{T} \frac{PC_t}{(1+r)^t},$$ (F2)

where PC   is $C_{Est} + C_{O\&M} + C_{MGMT}$,
       t is time,
       T is the terminal year for the mitigation activity,
       r is a discount rate,
       C_{Est} are periodically recurring capital costs, including annual land rental payments and other initial investment costs required in establishing the management activity,

$C_{O\&M}$ are annual operating and maintenance costs of the activity with time, and

C_{MGMT} are annual and periodic management costs including administration, insurance, and other transaction costs.

Possible local combinations of soil quality and other land characteristics (nutrients, moisture, composition), access from roads, slope, aspect, water availability (precipitation, irrigation), plants (type, density, composition) can affect the costs of specific management activities. The data used in estimating the present value of costs are listed in table F1. These establishment and continuing costs occur at different times during the lifetime of a management activity.

The EAC in equation F3 is a conversion of the PVC into an annual value (Stavins and Richards, 2005):

$$EAC = PVC \times \left[\frac{r}{1-(1+r)^{-T}} \right], \tag{F3}$$

The stumpage value is estimated as follows:

$$W_{Mg(timber)/ha} = W_{C/ha} \times 2, \tag{F4}$$

$$W_{Mg(timber)/ha}^{Change} = W_{Mg(timber)/ha}^{ENH} - W_{Mg(timber)/ha}^{REF}, \tag{F5}$$

$$W_{Mg(timber)}^{Change} = W_{Mg(timber)/ha}^{Change} \times hectares, \tag{F6}$$

$$W_{Tons(timber)}^{Change} = W_{Mg(timber)}^{Change} \times 0.907, \tag{F7}$$

$$V_{timber} = W_{Tons(timber)}^{Change} \times \$/_{ton}, \text{ and} \tag{F8}$$

$$PVB = \sum_{t=1}^{T} \frac{V_{timber(t)}}{(1+r)^t}, \tag{F9}$$

where $W_{C/ha}$ is the weight of carbon in megagrams per hectare,

$W_{Mg(timber)/ha}$ is the weight of timber in megagrams per hectare,

$W_{Mg(timber)/ha}^{REF}$ is the weight of timber in megagrams per hectare for the reference case,

$W_{Mg(timber)/ha}^{ENH}$ is the weight of timber in megagrams per hectare for the enhanced case,

$W_{Mg(timber)/ha}^{Change}$ is the change in weight of timber in megagrams per hectare from the reference case to the enhanced case,

$W_{Mg(timber)}^{Change}$ is the total weight change for the areal unit,

$W_{Tons(timber)}^{Change}$ is the total tons of the change for the areal unit,

$\$/ton$ is the price of the timber commodity, and

V_{timber} is the economic value of the timber.

Table F1.   Establishment and other capital and operating costs for management activities in U.S. Environmental Protection Agency level III ecoregions 73 (Mississippi Alluvial Plain) and 74 (Mississippi Valley Loess Plains) (modified from Omernik, 1987; Omernik, 2004).

[Source: Huang and others, 2004; Brown and others, 2005; U.S. Department of Agriculture, 2010. ha, hectares; ha/yr, hectares per year]

Mitigation activity	Establishment (one-time costs)	Periodic	Annual
Afforestation, hardwood	Land[a] (fee simple if purchased)=$/ha Saplings and planting = $209/ha Site preparation = $145/ha Supervision = $109/ha	Herbicide application one time per year for 5 years = $72/ha Management update every 10 years = $38/ha Boundary maintenance every 10 years = $8/ha	Land rental price = $77 per ha/yr. Measuring, monitoring, and administration (for example, insurance) = $4 per ha/yr.
Afforestation, evergreen	Seedlings and planting = $281/ha Site preparation = $412/ha Herbicide site preparation = $731/ha Management (initial) = $18/ha	Management update every 10 years = $38/ha Boundary maintenance every 10 years = $8/ha Burning every 10 years = $150/ha	Land rental price = $77 per ha/yr. Measuring and monitoring administration (for example, insurance).
Grazing			Land rental price (or mortgage payments) = $77 per ha/yr. Management and administration = $37 per ha/yr.
Reforestation		Thinning every 15 years; fertilization every 15 years; and herbicide application 5th and 15th years = $912/ha	Management and administration.
No-till agriculture			Annuity payment = $22 per ha/yr to $48 per ha/yr.

[a]Price of rent per hectare at the time of the real-estate transaction. Land could be purchased through annual mortgage payments.

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[Reports that are only available online may require a subscription for access.]

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Appendix G. Methods for Validation and Uncertainty Assessment

G.1. Validation for the National Assessment

Within the context of the national assessment methodology, validation is defined as a quantitative evaluation of the quality of the input and (or) output data products upon which the assessment will be based. The validation strategy is designed to achieve two principal 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.

In terms of conducting validation for the assessment, potential errors underlying the assessment results can be attributed either to the input data products that are independent of the models or to model performance. The known accuracy of independent input data products, such as the National Land-Cover Datasets (NLCD), will be documented by referencing published reports—no new efforts are planned for validation

of these existing data products. Instead, the validation strategy is focused on new data products generated from assessment models.

G.1.1. General Approach

The methods employed in the national assessment involve numerous input and output variables, each of which represents a potential target for validation. The validation strategy recognizes that individual variables are not equally effective as validation targets and that each target must be selected with consideration to its relative importance for the assessment results and the availability and quality of reference data. These considerations led to the selection of 14 variables as both appropriate and feasible targets for validation. The selected target variables and their characteristics (measurement units, spatial and temporal attributes) are listed in table G1. The set consists predominately of end-point data products

Table G1. Major deliverable data products that will be targeted for validation and corresponding reference data sources for each deliverable.

[Abbreviations used in this table can be found in "Abbreviations, Acronyms, and Chemical Symbols" in the front of this report]

Deliverable product	Measurement units	Temporal validation targets	Reference data source	
			Existing	Prospective
Modeled land-cover and land-use change[1]	Thematic	2001–2010 estimates	LANDFIRE VCT	
Ecosystem disturbance (fire)[1]	Thematic	2001–2010 estimates	LANDFIRE MTBS, Consume outputs, NOAA CarbonTracker	
Delivery of water to coastal areas[1]	Cubic meters per month; cubic meters per year	2001–2010 estimates	USGS streamgage network	
Net ecosystem productivity by pools, ecosystems	Grams of carbon per square meter per year	2001–2010 estimates	AmeriFlux, NEON, NOAA CarbonTracker	
Net biome productivity	Grams of carbon per square meter per year	2001–2010 estimates	AmeriFlux, NEON, NOAA CarbonTracker	
Grain yields	Grams of carbon per square meter per year	2001–2010 estimates	USDA NASS, ARS	
Carbon stock by pools and ecosystems	Grams of carbon per square meter	2001–2010 estimates	FIA/RPA, LTER, NEON, ARS, GRACEnet	Aboveground biomass maps from LIDAR, SAR.
Carbon emission by wildland fire[1]	Grams of carbon per square meter per year	2001–2010 estimates	LANDFIRE MTBS with Consume	
Carbon removal by forest harvesting	Grams of carbon per square meter per year	2001–2010 estimates	Forest Service FIA	
Carbon pool size in lake and reservoir sediments	Grams of carbon per square meter	2010	RESIS–II, ad hoc reports	Impoundment maps from LIDAR, SAR, aerial imaging.
Carbon accumulation rate in lake and reservoir sediments	Grams of carbon per square meter per year	2010	RESIS-II	
Methane emission by ecosystems	Tons of CO_2e per square meter per year	2001–2010	AmeriFlux, NEON, NOAA CarbonTracker, ad hoc reports	
Nitrous-oxide emissions by ecosystems	Tons of CO_2e per square meter per year	2001–2010	AmeriFlux, ad hoc reports	
Carbon delivery by rivers to coastal areas	Grams of carbon per month; grams of carbon per year	2010	NWIS, SPARROW, NEWS	

[1]Intermediate product.

from the modeling of terrestrial and aquatic systems, but also includes key intermediate data products (land-use and land-cover change, ecosystem disturbance by fire).

Opportunities for validation fundamentally are constrained by the availability of suitable, existing reference datasets and resources to support new dataset development and implementation of validation tasks. The key factors that affect the suitability of a reference dataset are its inherent data quality and its correspondence with the spatial and temporal attributes of the target variable. As a general rule, the validation will draw upon the best available (most suitable) existing datasets produced independently of the national assessment activity and upon additional monitoring data as they become available. The reference datasets to be employed for initial validation are listed in table G1. The reference data sources are identified as existing or prospective. The prospective data sources represent data that are currently unavailable but could be developed in time to meet the needs of the assessment.

G.1.2. Sampling Strategy for Validation

A sampling approach to validation will be constructed to create a practical alternative to the time-consuming and expensive option of a full-coverage national validation using all potentially available validation data. The sampling approach will focus on a much smaller total area within which validation data can be selected, evaluated for quality, and processed for analyses. The probability sampling design underlying the validation will allow for rigorous inference to validate the full national assessment.

The rationale of the sampling approach is to spatially constrain the collection and processing of validation data. The candidate validation data from all carbon pools will be collected and the spatial co-location of these data will allow for analysis of associations among pools as well as within pools. The collection of validation data will not be restricted to the sample locations. For example, extremely valuable but sparse datasets, such as those available from FLUXNET, will be used in their entirety. Data of known quality that are available across a broad spatial extent (for example, Forest Inventory and Analysis (FIA) and National Resources Inventory (NRI)) also may be used in their entirety for certain validation analyses. The sampling approach primarily is targeted for potential validation data that require thorough scrutiny to establish fitness for use.

The sampling design for validation will be stratified with each of the assessment units serving as a stratum. This will allow validation results to be reported by these assessment units (U.S. Environmental Protection Agency level II ecoregions, modified from Omernik, 1987). The sampling unit within each ecoregion will be a county, and a sample of counties will be selected within an ecoregion. A further stratification within each region will be constructed using criteria defining a priority of interest. That is, counties exhibiting large model uncertainties, high quantities of land-cover change, or containing rare conditions (for example, estuaries, wetlands,

or impoundments) may be sampled with greater probability to increase the sample of validation data appropriate to address key questions. Potential validation data from any carbon pool then would be collected within the selected sample counties. In some cases, the validation data will have originated from a probability sampling design (for example, FIA and NRI reference data), and the desired probability-sampling feature of these validation data will be maintained. In other cases, the validation data will not have a rigorous sampling basis (for example, existing light detection and ranging (LIDAR) coverage), and the representation of the sample will be limited to the area of existing coverage.

The validation sampling design will be constructed to allow continuous augmentation of the sample to build the validation database as resources become available; however, the sampling design will ensure that defensible estimates can be obtained from the sample at any stage during the procurement of the validation database.

G.1.3. Quality Control and Quality Assurance

Validation is the cornerstone for quality control and quality assurance (QC/QA) in the national assessment and subsequent monitoring. The validation and modeling teams will coordinate a continual review of information from the validation activity to identify problems or deficiencies in model results. Inconsistencies in model results and reference data that are deemed significant or anomalous in space or time will be flagged for further investigation. The modeling teams will seek to identify and understand the factors that underlie such inconsistencies, define explicit strategies to reduce or resolve them, and whenever feasible, promptly implement those strategies. Thus, the QC/QA process is realized through a dynamic feedback loop in which the validation leads to improved understanding of the methodology performance, which in turn leads to improvements in the methodology design and implementation (data, models, sampling).

G.1.4. Relation Between Validation and Monitoring

The strategies for validation and monitoring in the national assessment methodology are closely coupled. The data requirements addressed by the monitoring strategy encompass those for validation. Thus, validation and QC/QA will be sustained in parallel with monitoring subsequent to the initial national assessment.

G.1.5. Adaptability of Validation Strategy

The validation strategy will be adaptable to changes in data availability and information requirements. Individual data products from the assessment (including intermediate ones) may be added or removed from the list of validation targets in response to changes in model performance or specific issues that may arise. Additional or improved datasets will

be incorporated as they become available and when deemed effective in support of validation objectives. The potential data sources identified in table G1 are recognized to have particularly strong potential for improving the reliability of the assessment results. In particular, implementation of LIDAR-based techniques for estimating aboveground biomass can be readily achieved through coordination of the growing set of planned and potential LIDAR-related activities of the U.S. Geological Survey (USGS) and other governmental or private organizations. The benefits and opportunities for incorporating LIDAR-derived biomass data in the national assessment are addressed below.

G.1.6. Addressing Data Gaps and Deficiencies: The Case of LIDAR

LIDAR technology of various configurations has been well demonstrated in the literature, beginning as early as the 1980s, to be effective in quantifying forest and nonforest structure (Lefsky and others, 2002; Lim and others, 2003). Current (2010) systems collect extremely accurate three-dimensional information at the meter level from airborne systems and at the centimeter level from ground-based systems. The wealth of commercial and research sensors are providing three-dimensional data of vegetation structure at an unprecedented rate; however, there is not yet a capability that can provide the spatial and temporal coverage that space-based optical and radar systems offer. Whereas LIDAR has been used successfully on disparate projects across the country to quantify vegetation structure and biomass (Nelson and others, 2003), there is not a coordinated, concerted effort to collect systematic, standardized LIDAR-derived structural information for a national-scale biomass estimation, validation, and quantification of change.

G.2. Uncertainty Assessment

Although the validation process evaluates the quality of output products based on comparison with existing data, uncertainty assessment builds on this by estimating confidence bounds on estimates that cannot be validated; for example, projections into the future or estimates for which there are no existing validation data. Assessing complex socioenvironmental systems generally contains some uncertainty resulting from data gaps, modeling capabilities, interactions between ecological phenomena, and our scientific understanding of the mechanics of these complex systems. It is essential for users of the national assessment to be aware of the many uncertainties inherent in methods and assumptions used. It is useful to distinguish between quantifiable uncertainties where some form of statistical information is available and nonquantifiable uncertainties where such information is not available. Because the latter are more difficult to analyze explicitly, the basic strategy will be to treat these uncertainties separately in terms of a two-level approach, based roughly on the

Intergovernmental Panel on Climate Change (IPCC) guidelines (Intergovernmental Panel on Climate Change, 2006).

G.2.1. Communication About Unquantifiable Uncertainties

The first-level uncertainty assessment is designed to incorporate unquantifiable uncertainties (designated as "unpredictabilities" by the IPCC) in terms of a representative set of scenarios to be modeled. These scenarios will be constructed to capture the relevant variability range in those factors deemed most important for carbon sequestration (including climate changes and population growth). There is no attempt to assign probabilities to different scenarios or storylines; they simply serve as examples of potential future conditions that might reasonably be expected to occur under different sets of assumptions about future environments and behavior; however, by adopting these different sets of assumptions, it is possible to model the carbon and greenhouse-gas (GHG) outcomes with measurable levels of uncertainty. Thus, these scenarios represent a set of uncertainty bounds on our assumptions about future conditions.

For this assessment, three of the major storylines proposed by the IPCC (Nakicenovic and others, 2000) will be followed, within which alternative management and mitigation scenarios are proposed (section 3.2 of this report). Uncertainty related to scenarios is considered unpredictable; hence, a strategy for communicating such uncertainty is needed. The communication effort will focus on sources of uncertainties and their potential effect.

G.2.2. Uncertainty Sources of Reference Scenarios and Potential Reduction Measures

Scenarios are useful tools to provide a range of potential future alternatives. This assessment will develop national and regional reference scenarios (section 3.2 of this report) that are consistent with IPCC storylines. The Special Report on Emission Scenarios (SRES) identified six primary sources of uncertainty within the scenarios framework (Nakicenovic and others, 2000). The same sources of uncertainty also are contained in the use of reference as well as alternative management scenarios developed for the assessment. The six sources are listed below.

Choice of storylines.—This category describes the uncertainty associated with the characteristics of the storylines and mostly is related to the combination of quantitative assumptions, such as increased population growth and decreased economic growth, used for each storyline.

Authors' interpretation of storylines.—Differences in the translation of qualitative storylines into quantitative drivers can introduce uncertainty into the storylines. Uncertainty may be reduced for harmonized drivers (population, gross domestic product) if parameters for drivers are chosen consistently with the storylines.

Translation of knowledge about driving forces into quantitative inputs for scenario analysis.—Understanding the links between the drivers and the quantifiable input parameters for models is limited and often results in an inconsistent application across modeling efforts.

Methodological differences.—These uncertainties arise from the modeling structure as well as the underlying uncertainties between drivers and their resulting effects.

Different sources of data.—Source data, such as land-use histories and baseline conditions, often are inconsistent in their availability (both spatially and temporally).

Inherent uncertainties.—Events considered "rare" are not included in modeling efforts because of their inherent unpredictability. Nonetheless, rare events have the ability to affect future trajectories and produce considerably different outcomes.

G.2.3. Uncertainties of Alternative Mitigation Scenarios and Potential Reduction Measures

As noted above, uncertainties around the IPCC SRES storylines and interpretation of them also apply to the alternative management scenarios for the same storylines. Here, a key uncertainty involves the design and implementation of future policies. Policies will affect eligibility for incentives, and policy instruments will motivate change to various degrees. Because of these concerns, direct prediction of future potential policies is not considered for the methodology in order to avoid increasing uncertainty. Instead, alternative management scenarios are linked with interpretation of plausible land-management activities. Sources of uncertainty and potential reduction measures relevant to alternative scenario development are given below.

Estimates of rates, suitable lands, and timing.—Uncertainties in the mitigation estimates can be improved by broadly incorporating expert knowledge at the regional and subregional level. Improving the spatial footprint by incorporating region-specific expert knowledge in the scenarios should (at least in theory) help improve uncertainties. Additionally, the estimates also can be improved by increasing the thematic precision of the land-use, land-cover, and land-management information (for example, managed loblolly pine forest versus softwood forest in the Southeastern United States). Increased thematic precision has ramifications for data requirements and availability and increases the cost of the analysis.

The evaluation of management activities for cost, ecosystem effects, energy usage, and technological progress.—The uncertainties of a management activity's performance are constrained by the use of relative, rather than absolute, estimates. Again, extensive consultation at the regional and subregional level will help.

Behavioral responses assumed in developing the scenarios.—Such uncertainties may be captured or reduced by comparing the results of a scenario development with the results of a biogeochemical simulation and, more effectively,

by monitoring or repeating assessments that revisit behavioral responses.

G.2.4. Estimation for Quantifiable Uncertainties

The second type of uncertainty treatment involves the explicit modeling of potential carbon sequestration for different scenarios. From a spatial perspective, the key objective of these models will be to downscale the parameters of each scenario (such as overall climatic conditions and population pressures) to grid cells that are small enough to allow explicit carbon-sequestration modeling. At this level of modeling, it is deemed that all uncertainties should be treated in a quantifiable way. It is important to distinguish between "value" uncertainty of input data and model parameters, uncertainty of model structure and mathematical processes, and uncertainty affected by other technical components of the methodology such as land-use and land-cover change and disturbance modeling. All value uncertainties will be treated as probability distributions that can serve as inputs to model simulations. Where statistical data are available, such distributions will be estimated by standard statistical procedures based on IPCC recommendations (Intergovernmental Panel on Climate Change, 2006). Otherwise, such distributions will be elicited through expert judgments (typically triangular distributions based on elicited value ranges and most likely values).

G.2.5. Uncertainty of Input Data and Model Parameters

Following the IPCC (2006) guidance, uncertainty analysis will focus on random errors associated with input data and model parameters. The following steps will be followed during the assessment to evaluate and report this type of uncertainty.

Input data used for modeling—such as biophysical data (climate, soil), modeled data (wildland fire, land-use change), and expert-knowledge-related data (mitigation activities)—will be assigned an uncertainty range, either expressed as a probability distribution function (PDF) curve or a probability look-up table. Example approaches include the following.

Land-cover data.—Uncertainty in initial land-use and land-cover data may be expressed as a contingency table, which can be used to develop empirical distributions of possible land-cover types for individual pixels, based on misclassification rates (Prisley and Smith, 1987; Fang and others, 2006). These empirical distributions can be translated into initial carbon-density distributions (Quaife and others, 2008).

Forest age and biomass.—Parameters used for initializing the biogeochemical modeling are based on the FIA program. Plot-level data can be aggregated based on location to the level of the Joint Frequency Distribution (JFD) unit used in biogeochemical methods. Aggregation can provide distributions for parameters such as forest age, biomass, species groups, site quality, canopy density, and so on.

Soil parameters.—Using the tables associated with the Soil Survey Geographic (SSURGO) database, it is possible to obtain ranges and distributions for important soil parameters based on the present soil components and their relative frequency.

Using approaches such as those outlined above or an empirical distribution (probability look-up table), similar to the fractile distribution shown in figure G1, input data distributions can be fit to mathematically defined statistical distributions, such as those described by IPCC (2006).

If a model parameter has a PDF, it can be evaluated using error propagation. When a parameter PDF is not available, it is possible to derive one using data-assimilation techniques. Some parameters may be obtained from expert judgment. For example, PDF parameters for remote-sensing-based fire-severity modeling may be obtained from table D2 in appendix D.

As input data are processed by models, additional opportunities arise to evaluate uncertainty. For example, the "forecasting scenarios of land-cover change" model (FORE–SCE) (appendix B of this report) uses logistic regression to predict probabilities of individual types of land-cover transitions. The result is a suite of probability surfaces representing the most likely locations for different types of changes to occur. Landcover changes are then allocated across a landscape. During this process, information on uncertainty is available from fit statistics for the regression models (Hosmer and Lemeshow, 2000), as well as from the probability surfaces (Dendoncker and others, 2008). For example, comparing the probabilities for different types of change at a given pixel can indicate how much more likely one type of change is than another. When probabilities for several types of change are similar, there is greater uncertainty and ambiguity as to the type of change that will occur.

It should be noted, however, that the focus of the uncertainty analysis will be on quantifying the variability of end results, which will be carbon storage and GHG fluxes. Uncertainties may arise during many parts of the modeling process that may have little effect on the final outcome. For example, the specific location of land-cover changes across a homogeneous landscape may be extremely uncertain, but also may make a minimal difference in overall long-term carbon sequestration at the reporting-unit level.

G.2.6. Uncertainty of Model Structure and Component Interactions

Structural and other conceptual uncertainties will be treated using model-run evaluation and expert judgment. One issue that the assessment should address is which biogeochemical models to use for which ecosystems, and which key carbon-, nutrient-, and water-cycle elements will be treated by the models. This will be determined on the basis of a criteria evaluation process outlined in chapter 3 of this report. Although it is possible to use alternative modeling forms in principle, it is deemed most practical from an operational perspective to consistently use the biogeochemical (BGC) models most recommended by experts. In doing so, it is vital that all assumptions be made explicit to model users. In addition, model sensitivities to key assumptions will be evaluated by simulations, and results made available to users. Both of these analyses can be tracked using a spreadsheet, which will be adopted for the entire assessment to track results and enhance user transparency.

For other conceptual uncertainties—such as the effects of climate change on disturbances and land-use and land-cover changes, or the interactions between the carbon, nutrient, and water cycles—statistical techniques such as the use of the IPCC-recommended PDF and Monte Carlo resampling methods may be used to understand the size of their uncertainties and relations between different ecosystem processes.

Because the General Ensemble Modeling System (GEMS) can encapsulate multiple models, and parameterize and drive these models with the same data, it provides an ideal environment or platform to identify and address issues of uncertainty related to model structure and mathematical representations of biophysical processes. For this assessment, model comparisons
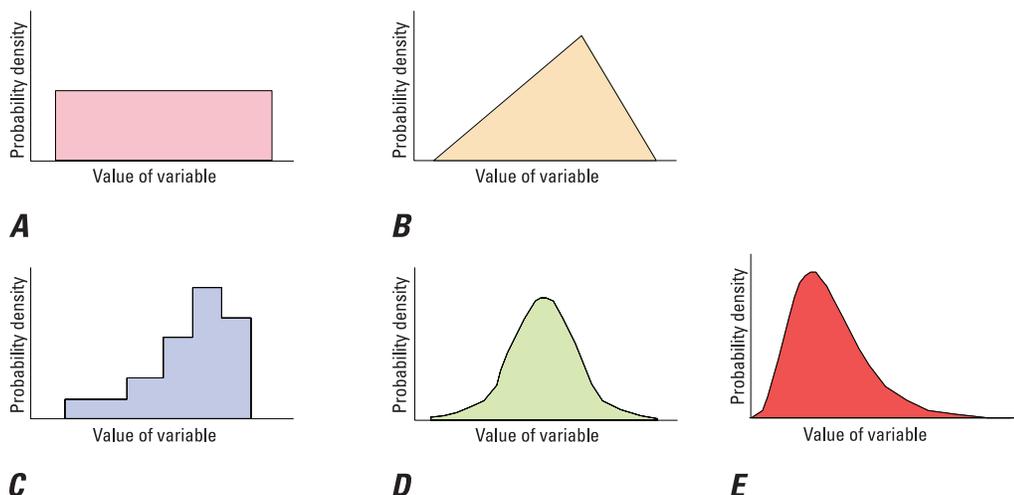

Figure G1. Typical probability distribution (density) function (PDF) curves. *A*, Uniform; *B*, Triangle; *C*, Fractile; *D*, Normal; *E*, Lognormal. Modified from Intergovernmental Panel on Climate Change (2006, p. 3.25), used with permission.

will be used within the GEMS structure and with other modeling groups via a national workshop. Additionally, to reduce biases in modeling, the models will be calibrated with in situ data (for example, flux-tower data, FIA data).

G.2.7. Uncertainty Related to Specific Methods

The assessment is required by the Energy Independence and Security Act (EISA) (U.S. Congress, 2007) to consider ecosystem-controlling processes, such as wildland fire, land-use change, lateral transport, and agricultural practices. The use of explicitly mapped and modeled ecosystem-controlling processes on a national basis for carbon sequestration and GHG fluxes should improve upon uncertainties in assessment results (Running, 2008), but it also is possible that the incorporation of such information could introduce new uncertainties into the methodology. Uncertainties related to the ecosystem-controlling processes will be quantified and reported. The basic approach for assessing such uncertainties is related to developing synthesis information and data products in support of formulating mitigation strategies. This approach is discussed in chapter 3 and appendix F of this report.

G.2.8. Increasing User Confidence by Delivering and Comparing Results

Analyzing uncertainties associated with model inputs and model construction provides useful information, but from the user's perspective, uncertainties generally are most easily communicated in terms of model outputs. The validation process described previously, when communicated together with uncertainty analysis, will help enhance user confidence about the input scenarios and data or model uncertainties. An important aspect of communicating the results and their uncertainties will be the ability to draw comparisons between the results of this assessment and other published projections of terrestrial carbon sequestration. For example, the validation plan includes a comparison of assessment results with the spatial and temporal distribution of terrestrial sources and sinks of atmospheric carbon estimated by the biosphere and fire modules of the National Oceanic and Atmospheric Administration's CarbonTracker system (table G1; Peters and others, 2007; National Oceanic and Atmospheric Administration, 2010). Highlighting differences between approaches, assumptions, data sources, and modeling techniques used in this assessment and other published works will help place the assessment results in perspective.

An additional means for communicating results to users is the delivery of assessment products in digital map format. The distribution of the maps through an online user interface (described in appendix I of this report) will allow users to obtain frequency distributions of the deliverables and an opportunity to explore these uncertainties in more depth (albeit, at different scales). It is also possible to provide summary measures of uncertainty based on all scenarios, such as overall value ranges (Intergovernmental Panel on Climate Change, 2006; fig. G2).
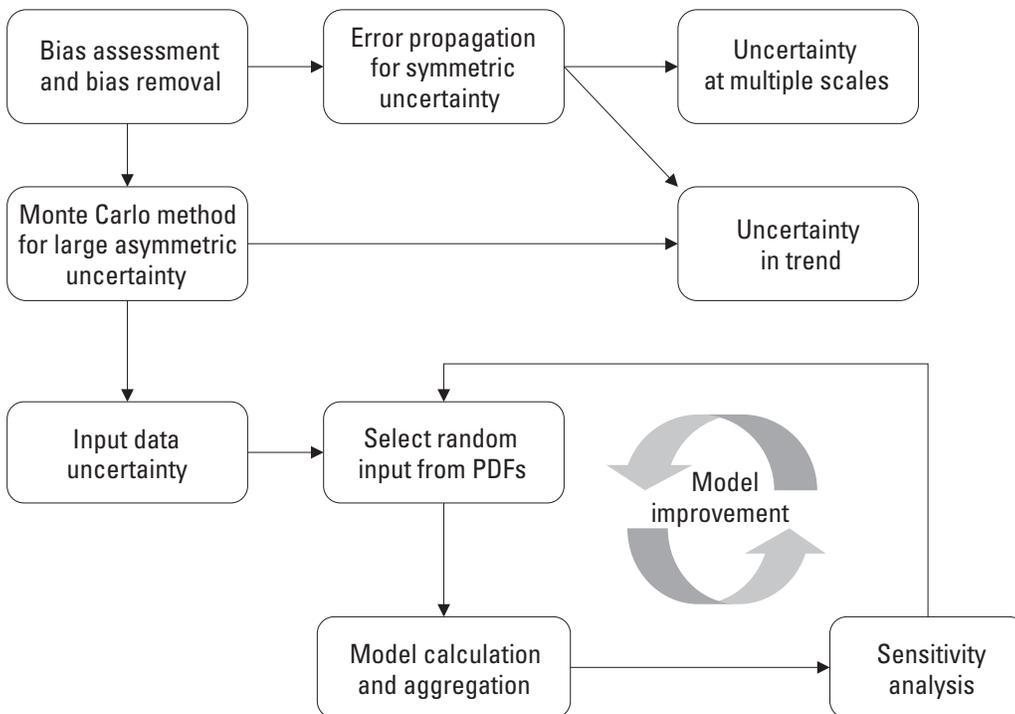

Figure G2. Diagram illustrating the recommended process for combining uncertainty from various sources in a carbon-sequestration assessment. PDF, probability distribution function.

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

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

H.1. Monitoring Objectives and Scope

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

- Provide ongoing, systematic quantification of carbon stocks, sequestration, GHG emissions, and related ecosystem properties and processes in the United States for the purpose of evaluating their status and trends.

- Aggregate and update observational monitoring data for the purpose of validation; for example, assessing the accuracy of model results.

- Provide a basis for evaluating the effectiveness of applied mitigation activities and strategies undertaken to reduce GHG emissions from ecosystems and promote carbon sequestration.

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

H.2. Definitions

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

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

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

H.3. Types of Resource Monitoring

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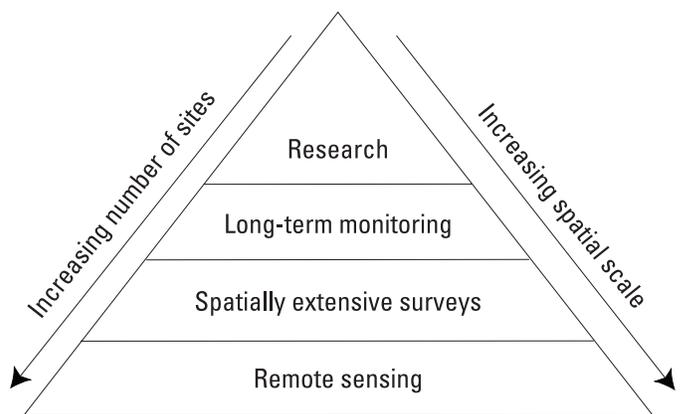

Figure H1. Diagram illustrating types of monitoring needed for assessing carbon sequestration and greenhouse-gas fluxes.

sensed data permit observation and assessment at regional to global scales. These data must be synthesized into a form that permits quantification over the spatial extent of the monitored area and analysis of change with time.

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

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

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

can be used to evaluate GHG sources and carbon sinks; spatial patterns in GHG concentrations in the atmosphere and oceans, for example, can be used to identify site characteristics that are useful for flux or carbon sequestration.

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

H.4. Existing Monitoring Data Sources

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

There is a strong need for coordination among the existing monitoring programs and data aggregation efforts to support the needs of the national assessment while avoiding a duplication of efforts. Several efforts are proposed or underway to aggregate some of the many types of data needed for regional- and national-scale monitoring into a consistent format, and to make it available

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

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

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

for general use, including the science-implementation strategy developed for the North American Carbon Program (Denning, 2005). In the absence of a robust and comprehensive data aggregation program housed within another Federal program, this role should be incorporated into the national assessment.

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

H.5. Major Monitoring Needs

H.5.1. Land Use and Land Cover

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

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

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

The task of monitoring carbon sequestration and GHG fluxes from vegetated surfaces can be achieved by using a combination of remote sensing and georeferenced plot data. Relative to other ecosystems, forests have far more extensive data-monitoring programs that are suitable for evaluating carbon sequestration and GHG fluxes. The USFS's FIA Program provides a rich database; new programs tasked with improving flux-tower networks and the characterization of vegetation structure, composition, and biomass are critically needed for urban forests, rangelands, and other nonforested systems, which occupy nearly 325 million hectares in the United States. The National Resources Inventory (NRI), administered by the Natural Resources Conservation Service (NRCS), collects such information, but the resulting data have been practically inaccessible; however, they could represent a valuable asset to the monitoring endeavor. Some systems, such

as the USDA's GRACEnet ("greenhouse gas reduction through agricultural carbon enhancement" network) and the American flux network (AmeriFlux), offer significant promise for monitoring nonforest landscapes and calibrating biogeochemical models, yet they are hardly extensive enough to provide estimates of carbon-sequestration estimates independently for entire landscapes. Likewise, a paucity of data exists describing belowground carbon dynamics, and this deficiency is a clear impediment to reliable estimates of belowground carbon sequestration through time. A more extensive network focused on belowground carbon dynamics is critical. In addition to field-based networks, more remote-sensing data suitable for characterizing vegetation attributes in nonforest landscapes are needed. Some high-resolution LIDAR sensors are available, which will undoubtedly be used to monitor vegetation conditions such as biomass and carbon stocks. The success of the monitoring of vegetated surfaces depends upon leveraging existing networks while developing new data-collection programs, especially in areas lacking sufficient data or exhibiting uncertainty.

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

H.5.2. Soil Carbon Stocks and Fluxes

It is suggested that the assessment will include the quantification of soil carbon stocks and fluxes from organic sources (for example, soil organic carbon (SOC), whereas only stock estimates will be provided from soil inorganic carbon (SIC) pools). Relative to other pools, soil-carbon observations are spatially and temporally sparse. SOC-flux estimates for grasslands and agricultural systems can be obtained from efforts such as those by Ogle and others (2007), which provides quantification of SOC in support of the EPA's official GHG estimates (U.S. Environmental Protection Agency, 2010). Additionally, the GRACEnet program (Jawson and others, 2005) offers a limited number of soil-carbon measurements in primarily agricultural landscapes. In the forest sector, the FIA program provides the most comprehensive forest soil-carbon-monitoring database available (O'Neill and others, 2005). Agency programs and those at research institutions

provide a suitable starting point for assimilating and aggregating SOC measures for monitoring purposes. Despite the paucity of programs offering measures of organic carbon components, those aimed at measuring inorganic components are even less numerous. Globally, SIC storage in arid and semiarid soils is approximately 2 to 10 times larger than SOC storage (Schlesinger, 1982; Eswaran and others, 2000). Annual fluxes from inorganic sources, however, are at least an order of magnitude smaller (U.S. Climate Change Science Program, 2007) than fluxes from organic sources. In addition, estimating fluxes from SIC are more difficult than estimating fluxes from SOC (Emmerich, 2003; Svejcar and others, 2008). Therefore, although SIC stocks will be estimated by using the Soil Survey Geographic database of the NRCS (SSURGO) and the State Soil Geographic Database of the NRCS (STATSGO; replaced in 2006 by the U.S. General Soil Map (STATSGO2)), no estimates of annual flux from SIC will be considered.

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

H.5.3. Aquatic Data

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

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

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

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

H.5.4. Priorities for New Data Collection

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

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

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

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

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Appendix I. Data Management Technical Plan

The national assessment of ecological carbon sequestration is based on a number of national capabilities including remote sensing, expert knowledge consultation, national inventory programs, land-use and land-cover maps, and simulation models. A data-processing, -management, and -serving system will be needed to provide the national assessment with data input, data output, information query and dissemination, and data-archive functionalities. The basic functions of the system should include the following:

- Remote-sensing data access
- Database building of expert knowledge of ecosystem processes and mitigation scenarios
- Database building of inventory and other in situ data (not the proprietary data held by national inventory programs such as the Forest Inventory and Analysis Program (FIA) of the U.S. Forest Service and the National Resources Inventory (NRI) of the Natural Resources Conservation Service)
- Climate, soil, and other biophysical data compilation required for the assessment
- Derived data storage, including geospatial data
- Table, chart, and report production
- Metadata production automation to the extent possible

This data-management system will consist of three subsystems: a data-storage subsystem; a data-conversion and integration subsystem; and a management, mapping, and reporting subsystem (fig. I1).
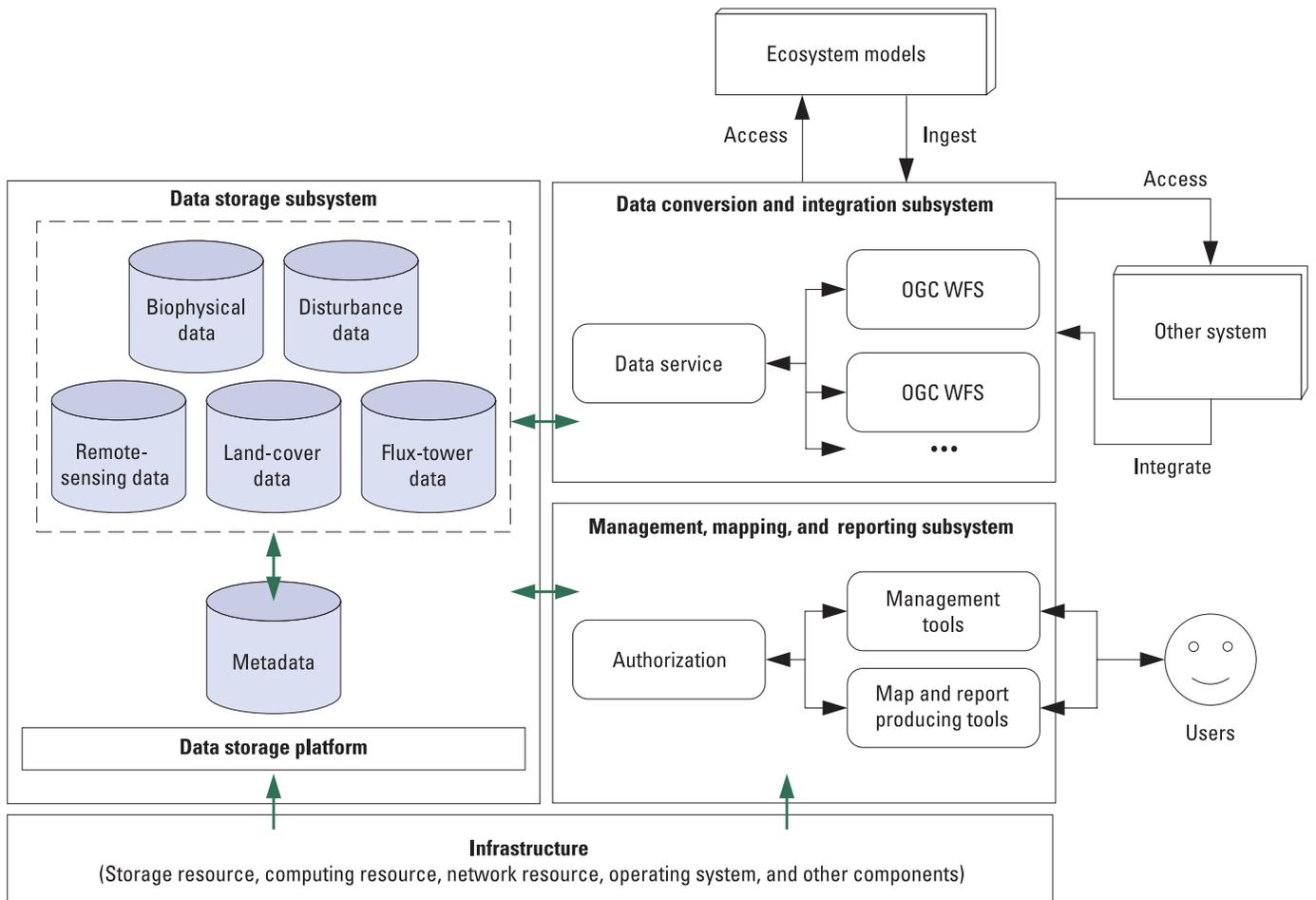

Figure I1. Diagram showing the overview of the proposed data-storage system for the national assessment of ecological carbon sequestration. OGC, Open Geospatial Consortium, Inc.; WCS, Web Coverage Service; WFS, Web Feature Service.

I.1. Data Storage Subsystem

The data-storage subsystem will be designed to support storage of data types with different spatial and temporal characteristics. Database software and hardware will be selected to provide the capability of handling large data volumes. An existing Sun Fire 4800 server running Oracle's Enterprise Edition Relational Database Management System (RDBMS) and the Environmental Systems Research Institute's (ESRI) Spatial Database Engine (ArcSDE) will be used for the prototype.

Storage of geospatial data and maps will be achieved by using geographic information system (GIS) database techniques. Spatial and nonspatial indexing will be used to enhance the performance of data searching and loading. The data-storage subsystem must be able to hold raster geospatial data, vector geospatial data, tabular data with no geospatial component, and text data.

The data-storage subsystem will be designed to handle the following datasets that will be collected from existing Federal programs:

- Remotely sensed images

- Vegetation, land-cover, land-use, and change maps

- Flux-tower data

- Climate, soil, and biophysical data

Other datasets will be added to the data-storage subsystem as they are identified as necessary components during the national carbon development assessment. Small to moderate data volumes will be ingested to demonstrate the abilities of this subsystem to handle complex ecosystem data. This subsystem also will provide storage for derived data from the model simulations, as well as maps and reports.

Metadata will be collected and stored in this subsystem. To ensure compatibility, the metadata structure will be designed following the standards of the International Organization for Standardization (ISO) and the Federal Geographic Data Committee (FGDC). This subsystem will be designed to synchronize metadata with associated data when new data are added or existing data are updated.

The Oracle database engine, coupled with ESRI's ArcSDE, will be able to store effectively all of the datasets and data types specified in this document. This data-storage solution is expandable to petabytes to accommodate the assessment requirements; a data-flow diagram is shown in figure I2.

I.2. Data Conversion and Integration Subsystem

The data-conversion and processing subsystem will be designed to provide key functions necessary for seamless integration of various datasets, including data and file-format conversion, reprojection, resampling, and other necessary geospatial transformations. These functions also will enable effective dissemination of results and data products derived through the national assessment. This subsystem will provide these functions via Web services for data access, exchange, and processing using standards-based interfaces. Open Geospatial Consortium, Inc. (OGC) and ISO data-service standards, such as Web Feature Service (WFS) and Web Coverage Service (WCS), will be adopted in the interface design. The interactive interfaces will allow other systems or clients to access the data through the Internet. In addition, this subsystem will provide capabilities for ingesting data from other remote data services and processing services. An overview of the processing subsystem is shown in figure I3.

For the prototype, OGC services will be provided by using ESRI's ArcGIS Server. The ESRI software for OGC services integrates seamlessly with Oracle and ArcSDE, and allows for minimal development efforts.
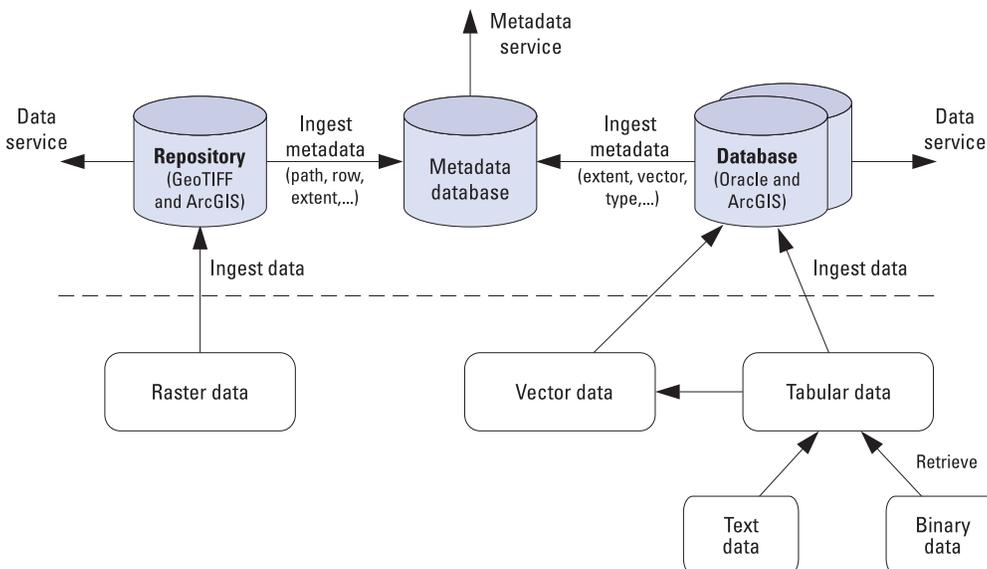

Figure I2. Data-flow diagram for the data-storage subsystem to be used for the national assessment of ecological carbon sequestration.
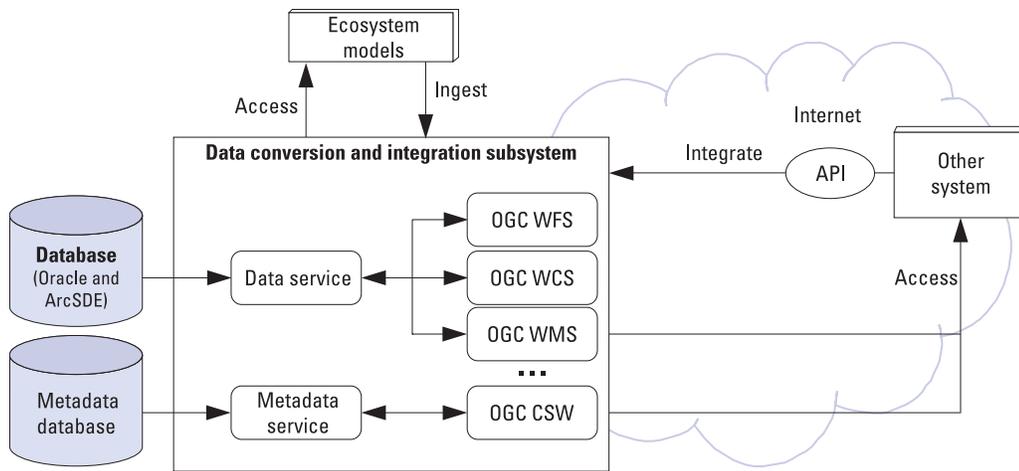
Figure I3. Diagram showing the data conversion and integration subsystem to be used for the national assessment of ecological carbon sequestration. API, application programming interface; ArcSDE, ESRI's Spatial Database Engine; CSW, Catalogue Service for Web; OGC, Open Geospatial Consortium, Inc.; WCS, Web Coverage Service; WFS, Web Feature Service; WMS, Web Map Service.

I.3. Management, Mapping, and Reporting Subsystem

The managing, mapping, and reporting subsystem will provide Web-based tools for users to view, search, and update their databases remotely. User authentication and access control will be implemented to enable secure data access and preserve data integrity. This subsystem also will provide functionalities for producing maps and reports using datasets collected by other Federal partners or produced through the national carbon assessment, or for extracting subsets of these data and saving them into a database or other desired formats. Web-based techniques will be used in developing this subsystem. The ESRI ArcGIS Server software product allows for Web-based delivery and custom tools to be developed.

I.4. System Technology Components

The planned system architecture is built on technology already in use at the Earth Resources Observation and Science (EROS) Center of the U.S. Geological Survey (USGS). The system architecture will use Oracle's Real Application Clusters (RAC) as its database, running ESRI's ArcSDE management software to add capacity for geospatial data. By leveraging Oracle RAC, the database subsystem can be spread across multiple systems and will provide increased availability and performance while using inexpensive commodity hardware.

USGS

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