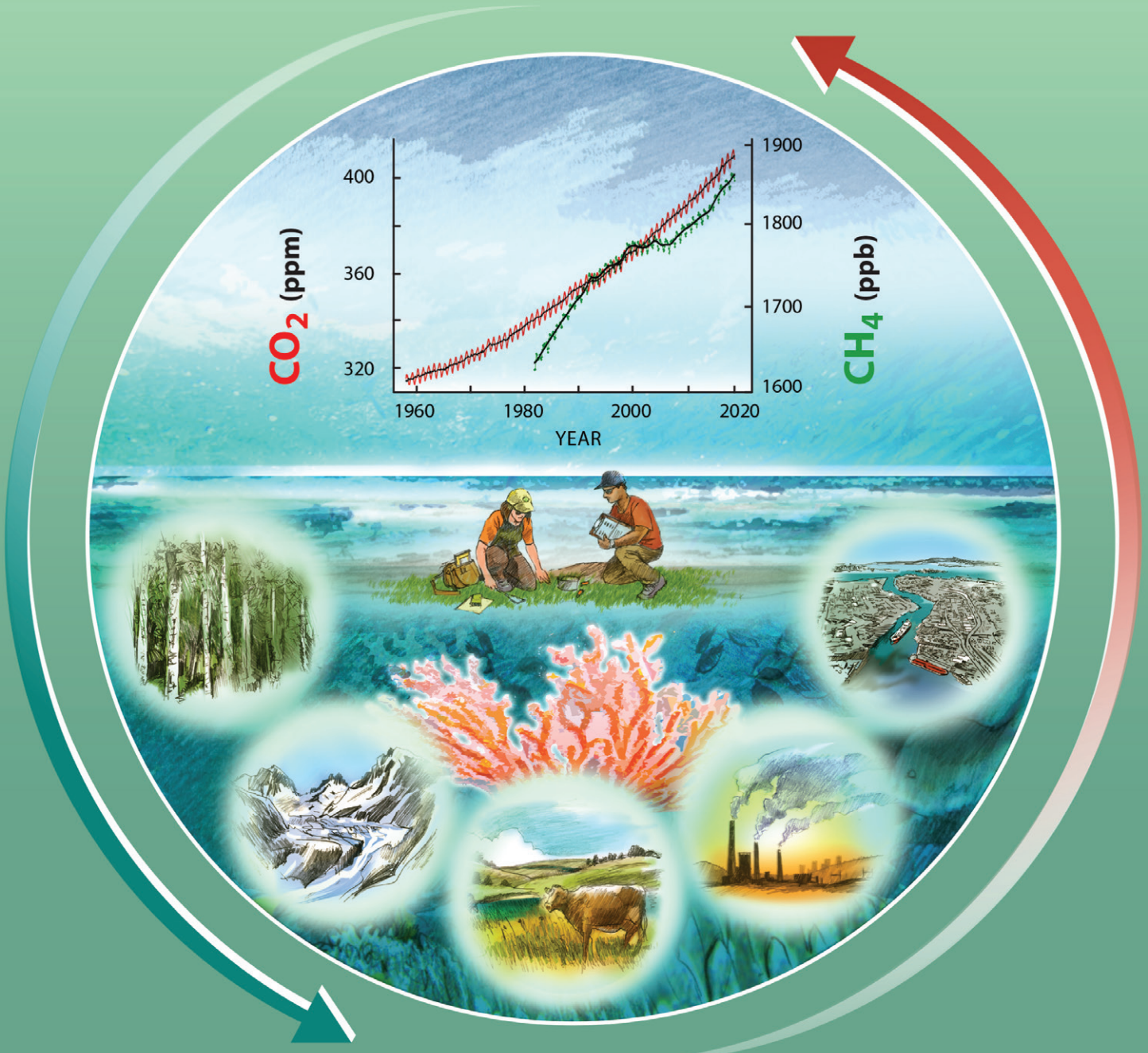
U.S. Global Change Research Program

Second State of the Carbon Cycle Report



A Sustained Assessment Report

Second State of the Carbon Cycle Report

A Sustained Assessment Report

U.S. Global Change Research Program

Report available online at carbon2018.globalchange.gov

This document does not express any regulatory policies of the United States or any of its agencies, or make any findings of fact that could serve as predicates of regulatory action. Agencies must comply with required statutory and regulatory processes before they could rely on any statements in the document or by the U.S. Global Change Research Program as basis for regulatory action.

This document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (P.L. 106-554) and information quality guidelines issued by the U.S. Department of Agriculture (www.ocio.usda.gov/document/usdas-peer-review-guidelines). This document was prepared and produced according to those guidelines and therefore is deemed a "highly influential scientific assessment" (HISA). The report graphics follow the ISO 19115 standard which includes the necessary information to achieve reproducibility.

The *Second State of the Carbon Cycle Report* (SOCCR2) is in the public domain. Some materials used herein are copyrighted, and permission was granted for their publication in this report. For subsequent uses that include such copyrighted materials, permission for reproduction must be sought from the copyright holder. In all cases, credit must be given for copyrighted materials. All other materials are free to use with credit to this report.

First published 2018

Recommended Citation for Report

USGCRP, 2018: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report* [Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 878 pp., https://doi.org/10.7930/SOCCR2.2018.

Front Cover

North American carbon cycling illustration, courtesy Ron Oden, University of Nevada, Reno.

This graphic represents the dynamic nature of carbon stocks and fluxes in the United States, Canada, and Mexico described in the *Second State of the Carbon Cycle Report*.

- The center sketch of researchers taking soil samples pays tribute to the hundreds of scientists who served as authors for this report and the thousands of researchers whose data were used throughout the document.
- Arrows depict carbon emissions to the atmosphere (red) and carbon uptake by different land types and aquatic environments (teal), processes described in Ch. 1: Overview of the Global Carbon Cycle and Ch. 2: The North American Carbon Budget.
- Plotted data—collected by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory—show monthly means of atmospheric carbon dioxide (CO_2) concentrations (red curve in parts per million) taken at the Mauna Loa Observatory and monthly means of methane (CH_4) concentrations (green curve in parts per billion) from globally averaged marine surface sites. Deseasonalized data are depicted by the black lines (Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane).
- Coral reefs, fish, and beaches represent carbon processes in coastal waters (Ch. 15: Tidal Wetlands and Estuaries and Ch. 16: Coastal Ocean and Continental Shelves). These are key areas experiencing carbon cycle changes due to direct effects of increasing CO_2 (Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide).
- Forests (first inset, lower left) and their soils represent the largest terrestrial carbon sink in North America. Factors influencing the strength of this sink and trends in disturbances such as wildfire, insects, and land-use change are described in Ch. 9: Forests.
- Mountains with melting glacier (second inset, lower left) illustrate the effects of greenhouse gas–induced warming on carbon cycling, particularly in high-latitude and boreal areas (Ch. 11: Arctic and Boreal Carbon).
- Pastoral scene (center inset, bottom) captures the interdependent carbon cycling processes among different terrestrial and aquatic systems (Ch. 5: Agriculture, Ch. 7: Tribal Lands, Ch. 10: Grasslands, Ch. 12: Soils, Ch. 13: Terrestrial Wetlands, and Ch. 14: Inland Waters).
- Power plant (second inset, lower right) illustrates carbon fluxes from the energy sector and other human systems and their potential impact on future carbon cycling (Ch. 3: Energy Systems and Ch. 19: Future of the North American Carbon Cycle).
- Coastal city and port (first inset, lower right) represent the many ways carbon is embedded in social systems and the different levels of information and governance involved in carbon decision making (Ch. 4: Understanding Urban Carbon Fluxes, Ch. 6: Social Science Perspectives on Carbon, and Ch. 18: Carbon Cycle Science in Support of Decision Making).

See inside back cover for image credits for chapter banners, section fronts, and back cover.

Carbon Cycle Interagency Working Group, SOCCR2 Federal Steering Committee, and SOCCR2 Federal Liaisons

*(*Federal Steering Committee member, ** Federal Liaison)*

Nancy Cavallaro,* USDA National Institute of Food and Agriculture; **Co-chair, Carbon Cycle Interagency Working Group; SOCCR2 Administrative Agency Lead**

Zhiliang Zhu,* U.S. Geological Survey; **Co-Chair, Carbon Cycle Interagency Working Group**

Daniel Stover,* DOE Office of Science

Marlen Eve,* USDA Agricultural Research Service

Noel P. Gurwick, U.S. Agency for International Development

Kathy Hibbard,* NASA Earth Science Division

Erica H. Ombres,* NOAA Ocean Acidification Program

Tom Wirth,* U.S. Environmental Protection Agency

James H. Butler,** NOAA Earth System Research Laboratory

Elisabeth Larson,** North American Carbon Program; NASA Goddard Space Flight Center, Science Systems and Applications Inc.

Laura Lorenzoni,** NASA Earth Science Division

Anne Marsh,** USDA Forest Service

Kathy Tedesco,** NOAA Ocean Observing and Monitoring Division; UCAR Cooperative Programs for the Advancement of Earth System Science

Paula Bontempi, NASA Earth Science Division

Gyami Shrestha,* **Ex officio as Lead SOCCR2 Development Advisor and Manager**; U.S. Carbon Cycle Science Program Office Director; Carbon Cycle Interagency Working Group; UCAR Cooperative Programs for the Advancement of Earth System Science

John Schade,* National Science Foundation

Chris Clark, U.S. Environmental Protection Agency

Dwight Gledhill, NOAA Ocean Acidification Program

Brad Reed, U.S. Geological Survey

Libby Jewett, NOAA Ocean Acidification Program

Randi Johnson, USDA National Institute of Food and Agriculture

Monika Kopacz, NOAA Atmospheric Chemistry, Carbon Cycle and Climate; UCAR Cooperative Programs for the Advancement of Earth System Science

Hank Margolis, NASA Earth Science Division

Kenneth Mooney, NOAA Atmospheric Chemistry, Carbon Cycle and Climate

Toral Patel-Weynand, USDA Forest Service

Luis Tupas, USDA National Institute of Food and Agriculture

James Whetstone, National Institute of Standards and Technology

Subcommittee on Global Change Research

Virginia Burkett, U.S. Department of the Interior (Acting Chair)

Gerald Geernaert, U.S. Department of Energy (Vice-Chair)

Michael Kuperberg, Executive Director, U.S. Global Change Research Program

John Balbus, U.S. Department of Health and Human Services

Pierre Comizzoli, Smithsonian Institution

Noel P. Gurwick, U.S. Agency for International Development

Wayne Higgins, U.S. Department of Commerce, NOAA

Scott Harper, U.S. Department of Defense (Acting)

William Hohenstein, U.S. Department of Agriculture

Jack Kaye, National Aeronautics and Space Administration

Dorothy Koch, U.S. Department of Energy

Andrew Miller, U.S. Environmental Protection Agency

James Riley, U.S. Department of the Interior

Gerald Solomon, U.S. Department of Transportation (Acting)

Trigg Talley, U.S. Department of State

Maria Uhle, National Science Foundation

Liaisons to the Executive Office of the President:

Chloe Kontos, Executive Director, National Science and Technology Council

Kimberly Miller, Office of Management and Budget

SOCCR2 Administrative Lead Agency

U.S. Department of Agriculture National Institute of Food and Agriculture

Science Leads

Richard Birdsey, Woods Hole Research Center

Melanie A. Mayes, Oak Ridge National Laboratory

Raymond G. Najjar, The Pennsylvania State University

Sasha C. Reed, U.S. Geological Survey

Paty Romero-Lankao, National Center for Atmospheric Research (currently at National Renewable Energy Laboratory)

Chapter Leads

Vanessa L. Bailey, Pacific Northwest National Laboratory

Lori Bruhwiler, NOAA Earth System Research Laboratory

David Butman, University of Washington

Wei-Jun Cai, University of Delaware

Abhishek Chatterjee, Universities Space Research Association; NASA Global Modeling and Assimilation Office

Sarah R. Cooley, Ocean Conservancy

Grant Domke, USDA Forest Service

Katja Fennel, Dalhousie University

Kevin Robert Gurney, Northern Arizona University

Daniel J. Hayes, University of Maine

Alexander N. Hristov, The Pennsylvania State University

Deborah N. Huntzinger, Northern Arizona University

Andrew R. Jacobson, University of Colorado, Boulder; NOAA Earth System Research Laboratory

Jane M. F. Johnson, USDA Agricultural Research Service

Randall Kolka, USDA Forest Service

Kate Lajtha, Oregon State University

Elizabeth L. Malone, Independent Researcher

Peter J. Marcotullio, Hunter College, City University of New York

Maureen I. McCarthy, University of Nevada, Reno; Desert Research Institute

A. David McGuire, U.S. Geological Survey; University of Alaska, Fairbanks

Anna M. Michalak, Carnegie Institution for Science; Stanford University

John B. Miller, NOAA Earth System Research Laboratory

David J. P. Moore, University of Arizona

Elise Pendall, Western Sydney University

Stephanie Pincetl, University of California, Los Angeles

Vladimir Romanovsky, University of Alaska, Fairbanks

Paty Romero-Lankao, National Center for Atmospheric Research (currently at National Renewable Energy Laboratory)

Edward A. G. Schuur, Northern Arizona University

Carl Trettin, USDA Forest Service

Rodrigo Vargas, University of Delaware

Tristram O. West, DOE Office of Science

Christopher A. Williams, Clark University

Lisamarie Windham-Myers, U.S. Geological Survey

Contributing Authors

Rose Abramoff, Lawrence Berkeley National Laboratory

Javier Alcocer, Universidad Nacional Autónoma de México

Simone R. Alin, NOAA Pacific Marine Environmental Laboratory

Andreas Andersson, Scripps Institution of Oceanography

Denis Angers, Agriculture and Agri-Food Canada

Dominique Bachelet, Oregon State University

Ashley Ballantyne, University of Montana

Sheel Bansal, U.S. Geological Survey

Leticia Barbero, NOAA Atlantic Oceanographic and Meteorological Laboratory

Sourish Basu, University of Colorado, Boulder; NOAA Earth System Research Laboratory

Brian Benscoter, Florida Atlantic University

Michele Betsill, Colorado State University

Sharon A. Billings, University of Kansas

Richard Birdsey, Woods Hole Research Center

Timothée Bourgeois, Dalhousie University

Scott Bridgham, University of Oregon

Molly E. Brown, University of Maryland

Lori Bruhwiler, NOAA Earth System Research Laboratory

David Butman, University of Washington

Nancy Cavallaro, USDA National Institute of Food and Agriculture

Darrel Cerkowniak, Agriculture and Agri-Food Canada

Abhishek Chatterjee, Universities Space Research Association; NASA Global Modeling and Assimilation Office

Mikhail Chester, Arizona State University

Rodney Chimner, Michigan Technological University

David W. Clow, U.S. Geological Survey

Richard T. Conant, Colorado State University

Sarah R. Cooley, Ocean Conservancy

John Coulston, USDA Forest Service

Felix Creutzig, Mercator Research Institute on Global Commons and Climate Change

Joseph Crosswell, Commonwealth Scientific and Industrial Research Organisation

Kenneth Davis, The Pennsylvania State University

Steven Davis, University of California, Irvine

Ben de Jong, El Colegio de la Frontera Sur

Daniel deB. Richter, Duke University

Paul del Giorgio, Université du Québec à Montréal

Stephen J. Del Grosso, USDA Agricultural Research Service

Scott Denning, Colorado State University

Yannis G. Dialynas, University of Cyprus (formerly at Georgia Institute of Technology)

Judith Drexler, U.S. Geological Survey

John Dunne, NOAA Geophysical Fluid Dynamics Laboratory

Kenneth H. Dunton, University of Texas, Austin

Riley Duren, NASA Jet Propulsion Laboratory

Bassil El Masri, Murray State University

Jill Engel-Cox, National Renewable Energy Laboratory

Wiley Evans, Hakai Institute

Richard A. Feely, NOAA Pacific Marine Environmental Laboratory

John Field, Colorado State University

Adrien Finzi, Boston University

Joshua B. Fisher, NASA Jet Propulsion Laboratory; California Institute of Technology

Lawrence B. Flanagan, University of Lethbridge

Guido Franco, California Climate Change Research Center

Nancy H. F. French, Michigan Technological University

Serita Frey, University of New Hampshire

Conor Gately, Boston University

Christopher Gough, Virginia Commonwealth University

Kevin Robert Gurney, Northern Arizona University

Noel P. Gurwick, U.S. Agency for International Development

Bob Haight, USDA Forest Service

Jennifer Harden, U.S. Geological Survey; Stanford University

Daniel J. Hayes, University of Maine

Jose Martin Hernandez-Ayon, Autonomous University of Baja California

Maria Herrmann, The Pennsylvania State University

Jeff Hicke, University of Idaho

Audra L. Hinson, Texas A&M University

Diana Hogan, U.S. Geological Survey

Charles S. Hopkinson, University of Georgia

Richard A. Houghton, Woods Hole Research Center

Jennifer Howard, Conservation International

Chuanmin Hu, University of South Florida

Xinping Hu, Texas A&M University, Corpus Christi

Sara Hughes, University of Toronto

Nathan Hultman, University of Maryland

Deborah N. Huntzinger, Northern Arizona University

Lucy R. Hutyra, Boston University

Andrew R. Jacobson, University of Colorado, Boulder; NOAA Earth System Research Laboratory

Maria Janowiak, USDA Forest Service

Henry Janzen, Agriculture and Agri-Food Canada

Jane M. F. Johnson, USDA Agricultural Research Service

Kristofer Johnson, USDA Forest Service

Zackary I. Johnson, Duke University

Daniel M. Kammen, University of California, Berkeley

Evan Kane, Michigan Technological University

Rene Kemp, Maastricht University

Chris Kennedy, University of Victoria

Gretchen Keppel-Aleks, University of Michigan

Alan K. Knapp, Colorado State University

Sara H. Knox, U.S. Geological Survey

Ken Krauss, U.S. Geological Survey

Kevin Kroeger, U.S. Geological Survey

Rob Krueger, Worcester Polytechnic Institute

Werner A. Kurz, Natural Resources Canada, Canadian Forest Service

David Lagomasino, University of Maryland

Elisabeth Larson, North American Carbon Program; NASA Goddard Space Flight Center, Science Systems and Applications Inc.

Johannes Lehmann, Cornell University

Jinxun Liu, U.S. Geological Survey

Shuguang Liu, Central South University of Forestry and Technology

Steven E. Lohrenz, University of Massachusetts, Dartmouth

Laura Lorenzoni, NASA Earth Science Division

Melissa Lucash, Portland State University

Yiqi Luo, Northern Arizona University

Loren Lutzenhiser, Portland State University

Michelle Mack, Northern Arizona University

Elizabeth L. Malone, Independent Researcher

Peter J. Marcotullio, Hunter College, City University of New York

Anne Marsh, USDA Forest Service

Melanie A. Mayes, Oak Ridge National Laboratory

Brian McConkey, Agriculture and Agri-Food Canada

Karis McFarlane, Lawrence Livermore National Laboratory

Emily McGlynn, University of California, Davis

A. David McGuire, U.S. Geological Survey; University of Alaska, Fairbanks

James McMahon, Better Climate Research and Policy Analysis

Patrick Megonigal, Smithsonian Environmental Research Center

Anna M. Michalak, Carnegie Institution for Science; Stanford University

John B. Miller, NOAA Earth System Research Laboratory

Umakant Mishra, Argonne National Laboratory

Mithra Moezzi, Portland State University

Siân Mooney, Arizona State University

David J. P. Moore, University of Arizona

William R. Morrow, III, Lawrence Berkeley National Laboratory

Frank Muller-Karger, University of South Florida

Raymond G. Najjar, The Pennsylvania State University

Ilissa B. Ocko, Environmental Defense Fund
Stephen Ogle, Colorado State University
Sara Ohrel, U.S. Environmental Protection Agency
Marcela Olguín-Álvarez, Consultant, SilvaCarbon Program
Scott Ollinger, University of New Hampshire
Lesley Ott, NASA Goddard Space Flight Center
Yude Pan, USDA Forest Service
David Paré, Natural Resources Canada, Canadian Forest Service
Diane Pataki, University of Utah
May-Linn Paulsen, Scripps Institution of Oceanography
Keith Paustian, Colorado State University
Fernando Paz Pellat, Colegio de Postgraduados Montecillo
Dorothy Peteet, NASA Goddard Institute for Space Studies
John Phillips, First Americans Land-Grant Consortium
Emily Pidgeon, Conservation International
Darren Pilcher, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington and NOAA
Emily J. Pindilli, U.S. Geological Survey
Christopher S. Potter, NASA Ames Research Center
Benjamin Poulter, NASA Goddard Space Flight Center
Yves Prairie, Université du Québec à Montréal
Benjamin L. Preston, RAND Corporation
Beverly Ramsey, Desert Research Institute; Wa-Hi-La, LLC
Peter Raymond, Yale University
Margaret H. Redsteer, University of Washington
Sasha C. Reed, U.S. Geological Survey
Charles W. Rice, Kansas State University
Curtis Richardson, Duke University
Lisa Robbins, University of South Florida
Paty Romero-Lankao, National Center for Atmospheric Research (currently at National Renewable Energy Laboratory)
Adam Rosenblatt, University of North Florida
C. Alan Rotz, USDA Agricultural Research Service
Benjamin R. K. Runkle, University of Arkansas
Joellen Russell, University of Arizona
David Sailor, Arizona State University
Upendra M. Sainju, USDA Agricultural Research Service
Christina Schädel, Northern Arizona University
Sean M. Schaeffer, University of Tennessee
Karina V. R. Schäfer, Rutgers University
Joshua Schimel, University of California, Santa Barbara
Abigail Seadler, NASA Earth Science Division
Elizabeth H. Shadwick, College of William & Mary
Cindy Shaw, Natural Resources Canada, Canadian Forest Service
Gyami Shrestha, U.S. Carbon Cycle Science Program; University Corporation for Atmospheric Research
Samantha Siedlecki, University of Connecticut
R. Howard Skinner, USDA Agricultural Research Service
Margaret Skutsch, Centro de Investigaciones en Geografía Ambiental
Carolyn Smyth, Natural Resources Canada, Canadian Forest Service
Sarah Stackpoole, U.S. Geological Survey
Nadja Steiner, Fisheries and Oceans Canada
Rob Striegl, U.S. Geological Survey
Adrienne J. Sutton, NOAA Pacific Marine Environmental Laboratory
Chris Swanston, USDA Forest Service
Yuki Takatsuka, Florida State University
Jim Tang, Marine Biological Laboratory
Wenwu Tang, University of North Carolina, Charlotte
Brian Tangen, U.S. Geological Survey
Kathy Tedesco, NOAA Ocean Observing and Monitoring Division; University Corporation for Atmospheric Research
Pamela Templer, Boston University
Katherine Todd-Brown, Pacific Northwest National Laboratory
Ralph Torrie, Canadian Energy Systems Analysis and Research Initiative
Carl Trettin, USDA Forest Service
Daniela Turk, Dalhousie University
Maria Tzortziou, City University of New York
Penny Vlahos, University of Connecticut
Mark Waldrop, U.S. Geological Survey
Anthony P. Walker, Oak Ridge National Laboratory
Zhaohui Aleck Wang, Woods Hole Oceanographic Institution
Elizabeth B. Watson, Drexel University
Dave Wear, USDA Forest Service
Tristram O. West, DOE Office of Science
Thea Whitman, University of Wisconsin, Madison
Kimberly Wickland, U.S. Geological Survey
Tom Wirth, U.S. Environmental Protection Agency
Christopher W. Woodall, USDA Forest Service
Rita M. S. Yu, University of Washington
Zhiliang Zhu, U.S. Geological Survey

Review Editors

Gil Bohrer, Ohio State University

Nathaniel A. Brunsell, University of Kansas

Francesca Cotrufo, Colorado State University

Marjorie Friederichs, Virginia Institute of Marine Science

Tara Hudiburg, University of Idaho

Marc G. Kramer, Washington State University, Vancouver

Rachel Melnick, USDA National Institute of Food and Agriculture

Christine Negra, Versant Vision

Emily J. Pindilli, U.S. Geological Survey

Adam J. Terando, U.S. Geological Survey

Nicholas Ward, Pacific Northwest National Laboratory

Report Production Team

(Based at Oak Ridge National Laboratory)

Holly Haun, Lead, SOCCR2 ORNL Production and Editorial Team

Kris Christen

Marilyn Langston

Sheryl Martin

Stacey McCray

Marissa Mills

Judy Wyrick

Brett Hopwood

Betty Mansfield, Group Leader

Acknowledgments

David Dokken, Julie Morris, Amrutha Elamparuthy, and **U.S. Global Change Research Program National Coordination Office Staff**

David Strong, Bergit Uhran, and U.S. Geological Survey **SOCCR2 Website 1.0 Developer Team**

Alison Crimmins, U.S. Environmental Protection Agency, and Meg Walsh, USDA Office of the Chief Economist for guidance during the initiation of the assessment process

Jennifer Bennett-Mintz, Laurel Gutenberg, Tess Carter, Anna Cram, Adam Stein, and Matt Stephens for assistance during development

Christopher DeRolph and Adam Malin, Oak Ridge National Laboratory, for graphics support

Former SOCCR2 Federal Steering Committee Members and Liaisons: Karina V. R. Schäfer (formerly National Science Foundation), Jared DeForest (formerly U.S. Department of Energy), Eric Kasischke (formerly NASA), Carolyn Olson (formerly USDA Office of the Chief Economist), Ben DeAngelo (formerly U.S. Global Change Research Program), and Glynis Lough (formerly National Climate Assessment, U.S. Global Change Research Program)

Canadian Science Liaisons: Catherine Ste-Marie, Geological Survey of Canada; Werner A. Kurz, Natural Resources Canada, Canadian Forest Service

Mexican Science Liaison: Fernando Paz Pellat, Colegio de Postgraduados Montecillo

NOAA National Centers for Environmental Information Technical Support Team, SOCCR2 Website 2.0, and Resource Site Help: David R. Easterling, Sarah Champion, Kate Johnson, Angel Li, Thomas K. Maycock, and Brooke C. Stewart

Expert Reviewers: Sam Baldwin, DOE Office of Energy Efficiency and Renewable Energy; Sarah Burch, Waterloo University; John Robinson, University of Toronto; Benjamin Sovacool, University of Sussex and Aarhaus University; Camille Stagg, U.S. Geological Survey; Hal Wilhite, University of Oslo; and Nicole Woolsey Biggart, University of California, Davis

Global Carbon Project

ICF International, Inc.

University Corporation for Atmospheric Research, Cooperative Programs for the Advancement of Earth System Science (UCAR CPAESS)