





The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States

U.S. Climate Change Science Program
Synthesis and Assessment Product 4.3

May 2008

FEDERAL EXECUTIVE TEAM

Acting Director, Climate Change Science Program: ..... William J. Brennan

Director, Climate Change Science Program Office: ..... Peter A. Schultz

Lead Agency Principal Representative to CCSP,
Director, Global Change Program Office,
U.S. Department of Agriculture: ..... William G. Hohenstein

Product Lead, Global Change Program Office,
U.S. Department of Agriculture: ..... Margaret K. Walsh

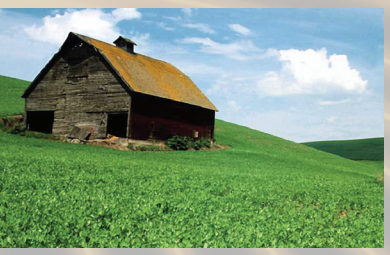
Chair, Synthesis and Assessment Product Advisory
Group, Associate Director, National Center for
Environmental Assessment, U.S. Environmental
Protection Agency: ..... Michael W. Slimak

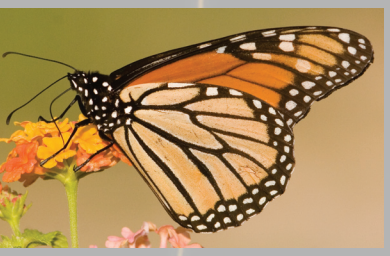
Synthesis and Assessment Product Coordinator,
Climate Change Science Program Office: ..... Fabien J.G. Laurier

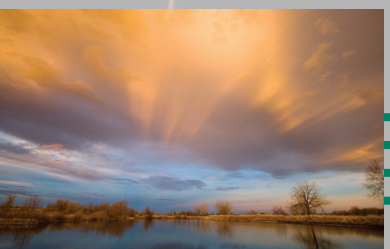
Special Advisor, National Oceanic and Atmospheric
Administration: ..... Chad A. McNutt

EDITORIAL AND PRODUCTION TEAM

Managing Editor, U.S. Department of Agriculture: ..... Margaret K. Walsh
Editorial Coordinator and Chapter Editor, NCAR: ..... Greg Guibert
Editorial Coordinator and Chapter Editor, NCAR: ..... Rachel Hauser
Publication and Graphics Coordinator, NCAR: ..... Carol Park
Layout Editor, NCAR: ..... Brian Bevirt
Scientific Editing and Review, NCAR: ..... Kathy Hibbard
Web support, NCAR: ..... Kristin Conrad
Web support, NCAR: ..... Steve Aulenbach
Web support, NCAR: ..... Erika Marcum
Graphic Design Support, Smudgeworks: ..... Michael Shibao
Technical Advisor, Climate Change Science Program Office: ..... David J. Dokken







The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States

Synthesis and Assessment Product 4.3
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

CONVENING LEAD AUTHORS:
Peter Backlund, Anthony Janetos, and David Schimel

MANAGING EDITOR:
Margaret Walsh

June 2008

Members of Congress:

On behalf of the National Science and Technology Council, the U.S. Climate Change Science Program (CCSP) is pleased to transmit to the President and the Congress this Synthesis and Assessment Product (SAP), *The Effects of Climate Change on Agriculture, Biodiversity, Land, and Water Resources in the United States*. This is part of a series of 21 SAPs produced by the CCSP aimed at providing current assessments of climate change science to inform public debate, policy, and operational decisions. These reports are also intended to help the CCSP develop future program research priorities. This SAP is issued pursuant to Section 106 of the Global Change Research Act of 1990 (Public Law 101-606).

The CCSP's guiding vision is to provide the Nation and the global community with the science-based knowledge needed to manage the risks and capture the opportunities associated with climate and related environmental changes. The SAPs are important steps toward achieving that vision and help to translate the CCSP's extensive observational and research database into informational tools that directly address key questions being asked of the research community.

This SAP assesses the effects of climate change on U.S. land resources, water resources, agriculture, and biodiversity. It was developed with broad scientific input and in accordance with the Guidelines for Producing CCSP SAPs, the Federal Advisory Committee Act, the Information Quality Act, Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (Public Law 106-554), and the guidelines issued by the Department of Agriculture to Section 515.

We commend the report's authors for both the thorough nature of their work and their adherence to an inclusive review process.

Sincerely,

Carlos M. Gutierrez
Secretary of Commerce
Chair, Committee on
Climate Change Science
and Technology Integration

Samuel W. Bodman
Secretary of Energy
Vice Chair, Committee on
Climate Change Science
and Technology Integration

John H. Marburger III
Director, Office of Science
and Technology Policy
Executive Director, Committee
on Climate Change Science and
Technology Integration

TABLE OF CONTENTS

Abstract VII

Executive Summary 1

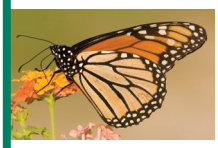
CHAPTER

1 11
Introduction

2 21
Agriculture

3 75
Land Resources: Forest and Arid Lands

4 121
Water Resources



5 151
Biodiversity

6 183
Synthesis

Appendix A: Acronyms and Glossary 194

Appendix B: References 197

RECOMMENDED CITATIONS

For the Report as a Whole:

CCSP, 2008: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. **P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M.G. Ryan, S.R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, R. Shaw**. U.S. Department of Agriculture, Washington, DC., USA, **362** pp

For the Executive Summary:

Backlund, P., A. Janetos, D.S. Schimel, J. Hatfield, M.G. Ryan, S.R. Archer, and D. Lettenmaier, 2008. **Executive Summary**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

For Chapter 1:

Backlund, P., D. Schimel, A. Janetos, J. Hatfield, M.G. Ryan, S.R. Archer, and D. Lettenmaier, 2008. **Introduction**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

For Chapter 2:

Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, and D. Wolfe, 2008. **Agriculture**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

For Chapter 3:

Ryan, M.G., S.R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, and W. Schlesinger, 2008. **Land Resources**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

For Chapter 4:

Lettenmaier, D., D. Major, L. Poff, and S. Running, 2008. **Water Resources**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

For Chapter 5:

Janetos, A., L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, and R. Shaw, 2008. **Biodiversity**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

For Chapter 6:

Schimel, D., A. Janetos, P. Backlund, J. Hatfield, M.G. Ryan, S.R. Archer, D. Lettenmaier, 2008. **Synthesis**. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, **362** pp

AUTHOR TEAM FOR THIS REPORT

Executive Summary	**Lead Authors**: Peter Backlund, NCAR; Anthony Janetos, PNNL/Univ. Maryland; David Schimel, National Ecological Observatory Network **Contributing Authors**: Jerry Hatfield USDA ARS; Mike G. Ryan, USDA Forest Service; Steven Archer, Univ. Arizona; Dennis Lettenmaier, Univ. Washington
Chapter 1	**Lead Authors**: Peter Backlund, NCAR; David Schimel, National Ecological Observatory Network; Anthony Janetos, PNNL/Univ. Maryland **Contributing Authors**: Jerry Hatfield USDA ARS; Mike G. Ryan, USDA Forest Service; Steven Archer, Univ. Arizona; Dennis Lettenmaier, Univ. Washington
Chapter 2	**Lead Author:** Jerry Hatfield, USDA ARS **Contributing Authors:** Kenneth Boote, Univ. Florida; Philip Fay, USDA ARS; Leroy Hahn, Univ. Nebraska; César Izaurralde, PNNL/Univ. Maryland; Bruce A. Kimball, USDA ARS; Terry Mader, Univ. Nebraska-Lincoln; Jack Morgan, USDA ARS; Donald Ort, Univ. Illinois; Wayne Polley, USDA ARS; Allison Thomson, PNNL/Univ. Maryland; David Wolfe, Cornell Univ.
Chapter 3	**Lead Authors:** Mike G. Ryan, USDA Forest Service; Steven Archer, Univ. Arizona **Contributing Authors:** Richard Birdsey, USDA Forest Service; Cliff Dahm, Univ. New Mexico; Linda Heath, USDA Forest Service; Jeff Hicke, Univ. Idaho; David Hollinger, USDA Forest Service; Travis Huxman, Univ. Arizona; Gregory Okin, Univ. California-Los Angeles; Ram Oren, Duke Univ.; James Randerson, Univ. California-Irvine; William Schlesinger, Duke Univ.
Chapter 4	**Lead Author:** Dennis Lettenmaier, Univ. Washington **Contributing Authors:** David Major, Columbia Univ.; Leroy Poff, Colo. State Univ.; Steve Running, Univ. Montana
Chapter 5	**Lead Author:** Anthony Janetos, PNNL/Univ. Maryland **Contributing Authors:** Lara Hansen, World Wildlife Fund Intl.; David Inouye, Univ. Maryland; Brendan P. Kelly, Univ. Alaska and National Science Foundation; Laura Meyerson, Univ. Rhode Island; Bill Peterson, NOAA; Rebecca Shaw, The Nature Conservancy
Chapter 6	**Lead Authors:** David Schimel, National Ecological Observatory Network; Anthony Janetos, PNNL/Univ. Maryland; Peter Backlund, NCAR; **Contributing Authors:** Jerry Hatfield USDA ARS; Mike G. Ryan, USDA Forest Service; Steven Archer, Univ. Arizona; Dennis Lettenmaier, Univ. Washington

ACKNOWLEDGEMENTS

In addition to the authors, many people made important contributions to this document.

Special thanks are due to Margaret Walsh of the USDA Climate Change Program Office. Her contributions to the report and the successful completion of this project are too numerous to document.

We are very appreciative of the excellent support from the project team at the University Corporation for Atmospheric Research (UCAR) and the National Center for Atmospheric Research (NCAR). From NCAR, Carol Park assisted with editing and research, and coordinated all aspects of the project; Greg Guibert and Rachel Hauser assisted with editing, technical writing, and research; Brian Bevirt contributed to editing and layout; and Kristin Conrad, Steve Aulenbach, and Erika Marcum provided web support. From the UCAR Communications Office, Nicole Gordon and Lucy Warner provided copy editing services. Michael Shibao of Smudgeworks provided graphic design services.

We are also grateful to the members of the Committee for the Expert Review of Synthesis and Assessment Product 4.3 (CERSAP) who oversaw the project on behalf of USDA and provided helpful guidance and insightful comments: Thomas Lovejoy (Heinz Center for Science, Economics, and the Environment), J. Roy Black (Michigan State University), David Breshears (University of Arizona), Glenn Guntenspergen (USGS), Brian Helmuth (University of South Carolina), Frank Mitloehner (UC Davis), Harold Mooney (Stanford University), Dennis Ojima (Heinz Center), Charles Rice (Kansas State University), William Salas (Applied Geosciences LLC), William Sommers (George Mason University), Soroosh Sorooshian (UC Irvine), Eugene Takle (Iowa State University), and Carol Wessman (University of Colorado).

Lawrence Buja (NCAR Climate and Global Dynamics Division (CGD) and Julie Arblaster (NCAR/CGD and the Australian Bureau of Meteorology) created and provided a series of figures showing projections of future climate conditions for the Introduction and Context chapter. Kathy Hibbard (NCAR/CGD) provided expert scientific input and review for the Biodiversity chapter. Timothy R. Green (Agricultural Engineer, USDA Agricultural Research Division) provided expert scientific input and review for aspects of the Water chapter. Chris Milly (USGS Continental Water, Climate, and Earth-System Dynamics Project), and Harry Lins (USGS Surface-water Program) also contributed to this chapter by providing figures 4.10 and 4.7, respectively. Figures 4.1 through 4.4 were prepared with assistance from Jennifer C. Adam (Washington State University). Authors in the Arid Land section of the Land Resources Chapter benefited from information generated by the Jornada and Sevilleta Long Term Ecological Research programs, and New Mexico's Experimental Program to Stimulate Competitive Research (EPSCoR). Julio Betancourt (USGS) provided valuable discussions on exotic species invasions. Craig Allen (USGS) provided the thumbnail image of Bandelier National Monument.

Finally, we wish to thank everyone who took the time to read and provide comments on this document during its various stages of review.

ABSTRACT

This report provides an assessment of the effects of climate change on U.S. agriculture, land resources, water resources, and biodiversity. It is one of a series of 21 Synthesis and Assessment Products (SAP) that are being produced under the auspices of the U.S. Climate Change Science Program (CCSP).

This SAP builds on an extensive scientific literature and series of recent assessments of the historical and potential impacts of climate change and climate variability on managed and unmanaged ecosystems and their constituent biota and processes. It discusses the nation's ability to identify, observe, and monitor the stresses that influence agriculture, land resources, water resources, and biodiversity, and evaluates the relative importance of these stresses and how they are likely to change in the future. It identifies changes in resource conditions that are now being observed, and examines whether these changes can be attributed in whole or part to climate change. The general time horizon for this report is from the recent past through the period 2030-2050, although longer-term results out to 2100 are also considered.

There is robust scientific consensus that human-induced climate change is occurring. Records of temperature and precipitation in the United States show trends consistent with the current state of global-scale understanding and observations of change. Observations also show that climate change is currently impacting the nation's ecosystems and services in significant ways, and those alterations are very likely to accelerate in the future, in some cases dramatically. Current observational capabilities are considered inadequate to fully understand and address the future scope and rate of change in all ecological sectors. Additionally, the complex interactions between change agents such as climate, land use alteration, and species invasion create dynamics that confound simple causal relationships and will severely complicate the development and assessment of mitigation and adaptation strategies.

Even under the most optimistic CO_2 emission scenarios, important changes in sea level, regional and super-regional temperatures, and precipitation patterns will have profound effects. Management of water resources will become more challenging. Increased incidence of disturbances such as forest fires, insect outbreaks, severe storms, and drought will command public attention and place increasing demands on management resources. Ecosystems are likely to be pushed increasingly into alternate states with the possible breakdown of traditional species relationships, such as pollinator/plant and predator/prey interactions, adding additional stresses and potential for system failures. Some agricultural and forest systems may experience near-term productivity increases, but over the long term, many such systems are likely to experience overall decreases in productivity that could result in economic losses, diminished ecosystem services, and the need for new, and in many cases significant, changes to management regimes.