GEOPHYSICAL MONOGRAPH SERIES

AGU
ADVANCING EARTH AND SPACE SCIENCE

Wetland Carbon and Environmental Management

Editors
Ken W. Krauss
Zhiliang Zhu
Camille L. Stagg

WILEY

GEOPHYSICAL MONOGRAPH SERIES

Wetland Carbon and Environmental Management

Ken W. Krauss, United States Geological Survey, USA
Zhiliang Zhu, United States Geological Survey, USA
Camille L. Stagg, United States Geological Survey, USA

Wetlands are vital natural assets, including their ability to take-up atmospheric carbon and restrict subsequent carbon loss to facilitate long-term storage. They can be deliberately managed to provide a natural solution to mitigate climate change, as well as to help offset direct losses of wetlands from various land-use changes and natural drivers.

Wetland Carbon and Environmental Management presents a collection of wetland research studies from around the world to demonstrate how environmental management can improve carbon sequestration while enhancing wetland health and function.

Volume highlights include:

- Overview of carbon storage in the landscape
- Introduction to wetland management practices
- Comparisons of natural, managed, and converted wetlands
- Impact of wetland management on carbon storage or loss
- Techniques for scientific assessment of wetland carbon processes
- Case studies covering tropical, coastal, inland, and northern wetlands
- Primer for carbon offset trading programs and how wetlands might contribute

The American Geophysical Union promotes discovery in Earth and space science for the benefit of humanity. Its publications disseminate scientific knowledge and provide resources for researchers, students, and professionals.

Cover Design: Wiley
Cover Image: © Illustration created by Laura S. Coplin, U.S. Geological Survey

www.wiley.com

Also available as an e-book

WILEY

AGU ADVANCING EARTH AND SPACE SCIENCE

ISBN 978-1-119-63928-2
90000
9 781119 639282

Geophysical Monograph Series

213 **Global Vegetation Dynamics: Concepts and Applications in the MC1 Model** *Dominique Bachelet and David Turner (Eds.)*
214 **Extreme Events: Observations, Modeling and Economics** *Mario Chavez, Michael Ghil, and Jaime Urrutia-Fucugauchi (Eds.)*
215 **Auroral Dynamics and Space Weather** *Yongliang Zhang and Larry Paxton (Eds.)*
216 **Low-Frequency Waves in Space Plasmas** *Andreas Keiling, Dong- Hun Lee, and Valery Nakariakov (Eds.)*
217 **Deep Earth: Physics and Chemistry of the Lower Mantle and Core** *Hidenori Terasaki and Rebecca A. Fischer (Eds.)*
218 **Integrated Imaging of the Earth: Theory and Applications** *Max Moorkamp, Peter G. Lelievre, Niklas Linde, and Amir Khan (Eds.)*
219 **Plate Boundaries and Natural Hazards** *Joao Duarte and Wouter Schellart (Eds.)*
220 **Ionospheric Space Weather: Longitude and Hemispheric Dependences and Lower Atmosphere Forcing Timothy Fuller-Rowell,** *Endawoke Yizengaw, Patricia H. Doherty, and Sunanda Basu (Eds.)*
221 **Terrestrial Water Cycle and Climate Change Natural and Human-Induced Impacts** *Qiuhong Tang and Taikan Oki (Eds.)*
222 **Magnetosphere-Ionosphere Coupling in the Solar System** *Charles R. Chappell, Robert W. Schunk, Peter M. Banks, James L. Burch, and Richard M. Thorne (Eds.)*
223 **Natural Hazard Uncertainty Assessment: Modeling and Decision Support** *Karin Riley, Peter Webley, and Matthew Thompson (Eds.)*
224 **Hydrodynamics of Time-Periodic Groundwater Flow: Diffusion Waves in Porous Media** *Joe S. Depner and Todd C. Rasmussen (Auth.)*
225 **Active Global Seismology** *Ibrahim Cemen and Yucel Yilmaz (Eds.)*
226 **Climate Extremes** *Simon Wang (Ed.)*
227 **Fault Zone Dynamic Processes** *Marion Thomas (Ed.)*
228 **Flood Damage Survey and Assessment: New Insights from Research and Practice** *Daniela Molinari, Scira Menoni, and Francesco Ballio (Eds.)*
229 **Water-Energy-Food Nexus – Principles and Practices** *P. Abdul Salam, Sangam Shrestha, Vishnu Prasad Pandey, and Anil K Anal (Eds.)*
230 **Dawn–Dusk Asymmetries in Planetary Plasma Environments** *Stein Haaland, Andrei Rounov, and Colin Forsyth (Eds.)*
231 **Bioenergy and Land Use Change** *Zhangcai Qin, Umakant Mishra, and Astley Hastings (Eds.)*
232 **Microstructural Geochronology: Planetary Records Down to Atom Scale** *Desmond Moser, Fernando Corfu, James Darling, Steven Reddy, and Kimberly Tait (Eds.)*
233 **Global Flood Hazard: Applications in Modeling, Mapping and Forecasting** *Guy Schumann, Paul D. Bates, Giuseppe T. Aronica, and Heiko Apel (Eds.)*
234 **Pre-Earthquake Processes: A Multidisciplinary Approach to Earthquake Prediction Studies** *Dimitar Ouzounov, Sergey Pulinets, Katsumi Hattori, and Patrick Taylor (Eds.)*
235 **Electric Currents in Geospace and Beyond** *Andreas Keiling, Octav Marghitu, and Michael Wheatland (Eds.)*
236 **Quantifying Uncertainty in Subsurface Systems** *Celine Scheidt, Lewis Li, and Jef Caers (Eds.)*
237 **Petroleum Engineering** *Moshood Sanni (Ed.)*
238 **Geological Carbon Storage: Subsurface Seals and Caprock Integrity** *Stephanie Vialle, Jonathan Ajo-Franklin, and J. William Carey (Eds.)*
239 **Lithospheric Discontinuities** *Huaiyu Yuan and Barbara Romanowicz (Eds.)*
240 **Chemostratigraphy Across Major Chronological Eras** *Alcides N.Sial, Claudio Gaucher, Muthuvairavasamy Ramkumar, and Valderez Pinto Ferreira (Eds.)*
241 **Mathematical Geoenergy:Discovery, Depletion, and Renewal** *Paul Pukite, Dennis Coyne, and Daniel Challou (Eds.)*
242 **Ore Deposits: Origin, Exploration, and Exploitation** *Sophie Decree and Laurence Robb (Eds.)*
243 **Kuroshio Current: Physical, Biogeochemical and Ecosystem Dynamics** *Takeyoshi Nagai, Hiroaki Saito, Koji Suzuki, and Motomitsu Takahashi (Eds.)*
244 **Geomagnetically Induced Currents from the Sun to the Power Grid** *Jennifer L. Gannon, Andrei Swidinsky, and Zhonghua Xu (Eds.)*
245 **Shale: Subsurface Science and Engineering** *Thomas Dewers, Jason Heath, and Marcelo Sánchez (Eds.)*
246 **Submarine Landslides: Subaqueous Mass Transport Deposits From Outcrops to Seismic Profiles** *Kei Ogata, Andrea Festa, and Gian Andrea Pini (Eds.)*
247 **Iceland: Tectonics, Volcanics, and Glacial Features** *Tamie J. Jovanelly*
248 **Dayside Magnetosphere Interactions** *Qiugang Zong, Philippe Escoubet, David Sibeck, Guan Le, and Hui Zhang (Eds.)*
249 **Carbon in Earth's Interior** *Craig E. Manning, Jung-Fu Lin, and Wendy L. Mao (Eds.)*
250 **Nitrogen Overload: Environmental Degradation, Ramifications, and Economic Costs** *Brian G. Katz*
251 **Biogeochemical Cycles: Ecological Drivers and Environmental Impact** *Katerina Dontsova, Zsuzsanna Balogh-Brunstad, and Gaël Le Roux (Eds.)*
252 **Seismoelectric Exploration: Theory, Experiments, and Applications** *Niels Grobbe, André Revil, Zhenya Zhu, and Evert Slob (Eds.)*
253 **El Niño Southern Oscillation in a Changing Climate** *Michael J. McPhaden, Agus Santoso, and Wenju Cai (Eds.)*
254 **Dynamic Magma Evolution** *Francesco Vetere (Ed.)*
255 **Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes** *Richard. E. Ernst, Alexander J. Dickson, and Andrey Bekker (Eds.)*
256 **Coastal Ecosystems in Transition: A Comparative Analysis of the Northern Adriatic and Chesapeake Bay** *Thomas C. Malone, Alenka Malej, and Jadran Faganeli (Eds.)*
257 **Hydrogeology, Chemical Weathering, and Soil Formation** *Allen Hunt, Markus Egli, and Boris Faybishenko (Eds.)*
258 **Solar Physics and Solar Wind** *Nour E. Raouafi and Angelos Vourlidas (Eds.)*
259 **Magnetospheres in the Solar System** *Romain Maggiolo, Nicolas André, Hiroshi Hasegawa, and Daniel T. Welling (Eds.)*
260 **Ionosphere Dynamics and Applications** *Chaosong Huang and Gang Lu (Eds.)*
261 **Upper Atmosphere Dynamics and Energetics** *Wenbin Wang and Yongliang Zhang (Eds.)*
262 **Space Weather Effects and Applications** *Anthea J. Coster, Philip J. Erickson, and Louis J. Lanzerotti (Eds.)*
263 **Mantle Convection and Surface Expressions** *Hauke Marquardt, Maxim Ballmer, Sanne Cottaar, and Jasper Konter (Eds.)*
264 **Crustal Magmatic System Evolution: Anatomy, Architecture, and Physico-Chemical Processes** *Matteo Masotta, Christoph Beier, and Silvio Mollo (Eds.)*
265 **Global Drought and Flood: Observation, Modeling, and Prediction** *Huan Wu, Dennis P. Lettenmaier, Qiuhong Tang, and Philip J. Ward (Eds.)*
266 **Magma Redox Geochemistry** *Roberto Moretti and Daniel R. Neuville (Eds.)*
267 **Wetland Carbon and Environmental Management** *Ken W. Krauss, Zhiliang Zhu, and Camille L. Stagg (Eds.)*

Geophysical Monograph 267

Wetland Carbon and Environmental Management

Ken W. Krauss
Zhiliang Zhu
Camille L. Stagg

Editors

This Work is a co-publication of the American Geophysical Union and John Wiley and Sons, Inc.

AGU
ADVANCING EARTH AND SPACE SCIENCE

WILEY

This edition first published 2022

Published under the aegis of the AGU Publications Committee

Matthew Giampoala, Vice President, Publications
Carol Frost, Chair, Publications Committee
For details about the American Geophysical Union visit us at www.agu.org.

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Krauss, Ken W., editor. | Zhu, Zhiliang (Physical scientist), editor. | Stagg, Camille L., editor.
Title: Wetland carbon and environmental management / Ken W. Krauss, Zhiliang Zhu, Camille L. Stagg, editors.
Description: Hoboken, NJ : Wiley, [2022] | Series: Geophysical monograph series | Includes index.
Identifiers: LCCN 2021027151 (print) | LCCN 2021027152 (ebook) | ISBN 9781119639282 (hardback) | ISBN 9781119639299 (adobe pdf) | ISBN 9781119639336 (epub)
Subjects: LCSH: Wetland management. | Carbon–Environmental aspects.
Classification: LCC QH75 .W4645 2022 (print) | LCC QH75 (ebook) | DDC 333.91/8–dc23
LC record available at https://lccn.loc.gov/2021027151
LC ebook record available at https://lccn.loc.gov/2021027152

Cover Design: Wiley
Cover Image: © Illustration created by Laura S. Coplin, U.S. Geological Survey

Set in 10/12pt Times New Roman by Straive, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

CONTENTS

Part IV Syntheses and Perspectives

LIST OF CONTRIBUTORS

Maria Fernanda Adame
Australian Rivers Institute
Griffith University
Nathan, QLD, Australia

Laura Aguirre-Franco
Red de Ecología Funcional
Instituto de Ecología A.C.
Veracruz, México

Michel Allenbach
Institut de Sciences Exactes et Appliquées
Université de la Nouvelle-Calédonie
New Caledonia, France

Frank E. Anderson
Land IQ, Inc.
Sacramento, California, USA

Virni B. Arifanti
Center for Socio-economic Policy and Climate Change Research
Ministry of Environment and Forestry
Bogor, Indonesia

Pascal Badiou
Institute for Wetland and Waterfowl Research
Ducks Unlimited Canada
Stonewall, Manitoba, Canada

Dennis D. Baldocchi
Department of Environmental Science, Policy, and Management
University of California
Berkeley, California, USA

Sheel Bansal
U.S. Geological Survey
Northern Prairie Wildlife Research Center
Jamestown, North Dakota, USA

Imam Basuki
Center for International Forestry Research
Bogor, Indonesia
and
Winrock International
Jakarta, Indonesia

María Belenguer-Manzanedo
Marine and Continental Waters
IRTA Institute of Agrifood Research and Technology
Barcelona, Spain
and
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Brian W. Benscoter
Department of Biological Sciences, and
Environmental Science Program
Florida Atlantic University
Davie, Florida, USA
and
Department of Energy
Earth and Environmental Systems Sciences Division
Washington, DC, USA

Brian A. Bergamaschi
U.S. Geological Survey
California Water Science Center
Sacramento, California, USA

Jennifer Bratchell
Department of Earth and Environmental Sciences
Macquarie University
Sydney, NSW, Australia
and
Lancaster Environment Centre
Lancaster University
Lancaster, UK

Mariana Bravo-Mendoza
Red de Ecología Funcional
Instituto de Ecología A.C.
Veracruz, México

Kristin B. Byrd
U.S. Geological Survey
Western Geographic Science Center
Moffett Field, California, USA

Antonio Camacho
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Alba Camacho-Santamans
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Nancy Cavallaro
U.S. Geological Survey
National Center
Reston, Virginia, USA

Luzhen Chen
Key Laboratory of the Ministry of Education for Coastal and Wetland Ecosystems
College of the Environment and Ecology
Xiamen University
Fujian, China

Jeffrey W. Cole
Latitude Climate
Boulder Creek, California, USA

Nicole Cormier
Department of Earth and Environmental Sciences
Macquarie University
Sydney, NSW, Australia
and
U.S. Geological Survey
Wetland and Aquatic Research Center
Lafayette, Louisiana, USA

Scott Covington
U.S. Fish and Wildlife Service
National Wildlife Refuge System
Falls Church, Virginia, USA

Rori Cowan
Radicle
San Francisco, California, USA

Irena F. Creed
School of Environment and Sustainability
University of Saskatchewan
Saskatoon, Saskatchewan, Canada

Andre Daniels
U.S. Geological Survey
Wetland and Aquatic Research Center
Davie, Florida, USA

Melanie J. Davis
U.S. Geological Survey
Oregon Cooperative Fish and Wildlife Research Unit
Corvallis, Oregon, USA

Susan E.W. De La Cruz
U.S. Geological Survey
Western Ecological Research Center
Moffett Field, California, USA

Amanda W.J. Demopoulos
U.S. Geological Survey
Wetland and Aquatic Research Center
Gainesville, Florida, USA

Judith Z. Drexler
U.S. Geological Survey
California Water Science Center
Sacramento, California, USA

Christopher S. Ellings
Nisqually Indian Tribe
Department of Natural Resources
Olympia, Washington, USA

Hangqing Fan
Guangxi Key Lab of Mangrove Conservation and Utilization
Guangxi Mangrove Research Center
Guangxi Academy of Sciences
Guangxi, China

Lola Fatoyinbo
Biospheric Sciences Laboratory
Earth Sciences Division
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA

Siobhan Fennessy
Environmental Studies and Biology Department
Kenyon College
Gambier, Ohio, USA

Etienne Fluet-Chouinard
Department of Earth System Science
Stanford University
Stanford, California, USA

Laura L. Flynn
Coastal Resources Group
Venice, Florida, USA

Andrew S. From
U.S. Geological Survey
Wetland and Aquatic Research Center
Lafayette, Louisiana, USA

Robert A. Gleason
U.S. Geological Survey
Northern Prairie Wildlife Research Center
Jamestown, North Dakota, USA

Connor Gorham
School of Science & Centre for Marine Ecosystems Research
Edith Cowan University
Joondalup, WA, Australia

Bayu Budi Hanggara
Center for International Forestry Research
Bogor, Indonesia

Lei He
Key Laboratory of Coastal Wetland Biogeosciences
Qingdao Institute of Marine Geology
China Geological Survey
Shandong, China

Kyle S. Hemes
Woods Institute for the Environment
Stanford University
Stanford, California, USA

Sayre Hodgson
Nisqually Indian Tribe
Department of Natural Resources
Olympia, Washington, USA

Gustaf Hugelius
Department of Physical Geography, and
Bolin Centre for Climate Research
Stockholm University
Stockholm, Sweden

Carles Ibáñez
Department of Climate Change
EURECAT, Technological Institute of Catalonia
Catalonia, Spain

Adrien Jacotot
Institut de Minéralogie de Physique des Matériaux et de Cosmochimie
Institut de Recherche pour le Développement
Sorbonne Université
New Caledonia, France
and
Institut de Sciences Exactes et Appliquées
Université de la Nouvelle-Calédonie
New Caledonia, France
and
Institut des Sciences de la Terre d'Orléans
Université d'Orléans
Orleans, France

Brita J. Jessen
Florida Department of Environmental Protection
Rookery Bay National Estuarine Research Reserve
Naples, Florida, USA

James Johnson
Environmental Science Program
Florida Atlantic University
Davie, Florida, USA
and
D. B. Warnell School of Forestry and Natural Resources
University of Georgia
Athens, Georgia, USA

Kuno Kasak
Department of Geography
Institute of Ecology and Earth Sciences
University of Tartu
Tartu, Estonia

Jeffrey J. Kelleway
School of Earth, Atmospheric and Life Sciences, and
GeoQuEST Research Centre
University of Wollongong
Wollongong, NSW, Australia

Randy Kolka
USDA Forest Service
Northern Research Station
Forestry Sciences Laboratory
Grand Rapids, Minnesota, USA

Charlie Koven
Climate and Ecosystem Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California, USA

Ken W. Krauss
U.S. Geological Survey
Wetland and Aquatic Research Center
Lafayette, Louisiana, USA

Kevin D. Kroeger
U.S. Geological Survey
Woods Hole Coastal and Marine Science Center
Woods Hole, Massachusetts, USA

Derrick Y. F. Lai
Department of Geography and Resource Management, and
Centre for Environmental Policy and Resource Management
The Chinese University of Hong Kong
Hong Kong SAR, China

Robert R. Lane
Comite Resources
Baton Rouge, Louisiana, USA

Ana Laura Lara-Domínguez
Red de Ecología Funcional
Instituto de Ecología A.C.
Veracruz, México

Paul S. Lavery
School of Science & Centre for Marine Ecosystems Research
Edith Cowan University
Joondalup, WA, Australia

Edward A. Laws
College of the Coast & Environment
Louisiana State University
Baton Rouge, Louisiana, USA

Iska Lestari
Department of Geophysics and Meteorology
Institut Pertanian Bogor University
Bogor, Indonesia

Qiulian Lin
Key Laboratory of the Ministry of Education for Coastal and Wetland Ecosystems
College of the Environment and Ecology
Xiamen University
Fujian, China

Tran Vu Khanh Linh
Department of Forest Resources Management
Faculty of Forestry
Nong Lam University
Ho Chi Minh City, Vietnam

Jorge López-Portillo
Red de Ecología Funcional
Instituto de Ecología A.C.
Veracruz, México

Sarah K. Mack
Tierra Foundation
New Orleans, Louisiana, USA
and
Tierra Resources
New Orleans, Louisiana, USA

Cyril Marchand
Institut de Minéralogie de Physique des Matériaux et de Cosmochimie
Institut de Recherche pour le Développement
Sorbonne Université
New Caledonia, France
and
Institut de Sciences Exactes et Appliquées
Université de la Nouvelle-Calédonie
New Caledonia, France

Maite Martínez-Eixarch
Marine and Continental Waters
IRTA Institute of Agrifood Research and Technology
Barcelona, Spain

Jennifer P. McClain-Counts
U.S. Geological Survey
Wetland and Aquatic Research Center
Gainesville, Florida, USA

J. Patrick Megonigal
Smithsonian Environmental Research Center
Edgewater, Maryland, USA

Javier Miralles-Lorenzo
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Daniel Morant
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Daniel Murdiyarso
Center for International Forestry Research
Bogor, Indonesia
and
Department of Geophysics and Meteorology
Institut Pertanian Bogor University
Bogor, Indonesia

Zachary Nagel-Tynan
School of Earth, Atmospheric and Life Sciences, and GeoQuEST Research Centre
University of Wollongong
Wollongong, NSW, Australia

Glynnis Nakai
U.S. Fish and Wildlife Service
Billy Frank Junior Nisqually National Wildlife Refuge
Olympia, Washington, USA

Scott C. Neubauer
Department of Biology
Virginia Commonwealth University
Richmond, Virginia, USA

Nguyen Thanh Nho
Faculty of Environmental and Food Engineering
Nguyen Tat Thanh University
Ho Chi Minh City, Vietnam

Nereida Núñez Álvarez
Centro de Investigación de Ciencias Ambientales
Universidad Autónoma del Carmen
Campeche, México

John Andrew Nyman
School of Renewable Natural Resources, and
Louisiana State University Agricultural Center
Louisiana State University
Baton Rouge, Louisiana, USA

Christopher J. Owers
Land and Water
Commonwealth Scientific and Industrial Research Organisation
Canberra, ACT, Australia

Susan E. Page
School of Geography, Geology & the Environment
University of Leicester
Leicester, UK

Brian A. Pellerin
U.S. Geological Survey
National Center
Reston, Virginia, USA

Rosela Pérez-Ceballos
Instituto de Ciencias del Mar y Limnología Estación El Carmen
Universidad Autónoma de México
Campeche, México

Antonio Picazo
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Emily J. Pindilli
U.S. Geological Survey
Science and Decisions Center
Reston, Virginia, USA

Benjamin Poulter
Biospheric Sciences Laboratory
Earth Sciences Division
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA

Lisa Reger
Environmental Science Program
Florida Atlantic University
Davie, Florida, USA

Carlos Rochera
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Kerrylee Rogers
School of Earth, Atmospheric and Life Sciences, and
GeoQuEST Research Centre
University of Wollongong
Wollongong, NSW, Australia

Judith A. Rosentreter
Centre for Coastal Biogeochemistry
School of Environment, Science and Engineering
Southern Cross University
Lismore, NSW, Australia

Neil Saintilan
Department of Earth and Environmental Sciences
Macquarie University
Sydney, NSW, Australia

Anna C. Santamans
Cavanilles Institute for Biodiversity and Evolutionary Biology
University of Valencia
Valencia, Spain

Meli Saragi-Sasmito
Center for International Forestry Research
Bogor, Indonesia

Sigit D. Sasmito
Center for International Forestry Research
Bogor, Indonesia
and
Research Institute for Environment and Livelihoods
Charles Darwin University
Darwin, NT, Australia

Oscar Serrano
School of Science & Centre for Marine Ecosystems Research
Edith Cowan University
Joondalup, WA, Australia

W. Barclay Shoemaker
U.S. Geological Survey
Caribbean Florida Water Science Center
Davie, Florida, USA

Gyami Shrestha
U.S. Global Change Research Program
U.S. Carbon Cycle Science Program Office
Washington, DC, USA

Frida Sidik
Institute for Marine Research and Observation
Ministry of Marine Affairs and Fisheries
Bali, Indonesia

Meriadec Sillanpää
Research Department
Green Forest Product and Technology Private Limited
Singapore

Matt J. Sirianni
Department of Geosciences
Florida Atlantic University
Davie, Florida, USA

Benjamin Sleeter
U.S. Geological Survey
Western Geographic Science Center
Tacoma, Washington, USA

Rachel R. Sleeter
U.S. Geological Survey
Water Mission Area
Reston, Virginia, USA

Lindsey S. Smart
Center for Geospatial Analytics
North Carolina State University
Raleigh, North Carolina, USA

Camille L. Stagg
U.S. Geological Survey
Wetland and Aquatic Research Center
Lafayette, Louisiana, USA

Ellen J. Stuart-Haëntjens
U.S. Geological Survey
California Water Science Center
Sacramento, California, USA

Zhinan Su
Guangxi Key Lab of Mangrove Conservation and Utilization
Guangxi Mangrove Research Center
Guangxi Academy of Sciences
Guangxi, China

Daphne Szutu
Department of Environmental Science, Policy, and Management
University of California
Berkeley, California, USA

Paul J. Taillie
Department of Wildlife Ecology and Conservation
University of Florida
Gainesville, Florida, USA

Brian A. Tangen
U.S. Geological Survey
Northern Prairie Wildlife Research Center
Jamestown, North Dakota, USA

Yancheng Tao
Key Laboratory of the Ministry of Education for Coastal and Wetland Ecosystems
College of the Environment and Ecology
Xiamen University
Fujian, China
and
Guangxi Key Lab of Mangrove Conservation and Utilization
Guangxi Mangrove Research Center
Guangxi Academy of Sciences
Guangxi, China

Muh Taufik
Department of Geophysics and Meteorology
Institut Pertanian Bogor University
Bogor, Indonesia

Nathan Thomas
Biospheric Sciences Laboratory
Earth Sciences Division
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA
and
Earth System Science Interdisciplinary Center
University of Maryland
College Park, Maryland, USA

Chuan Tong
Key Laboratory of Humid Subtropical Eco-Geographical Process, and School of Geographical Sciences
Fujian Normal University
Fujian, China

Carl Trettin
USDA Forest Service
Southern Research Station
Cordesville, South Carolina, USA

Bergit Uhran
U.S. Geological Survey
Florence Bascom Geoscience Center
Reston, Virginia, USA

Alex C. Valach
Department of Environmental Science, Policy, and Management
University of California
Berkeley, California, USA

Joe Verfaillie
Department of Environmental Science, Policy, and Management
University of California
Berkeley, California, USA

Truong Van Vinh
Department of Forest Resources Management
Faculty of Forestry
Nong Lam University
Ho Chi Minh City, Vietnam
and
Institut de Minéralogie de Physique des Matériaux et de Cosmochimie
Institut de Recherche pour le Développement
Sorbonne Université
New Caledonia, France
and
Institut de Sciences Exactes et Appliquées
Université de la Nouvelle-Calédonie
New Caledonia, France

Eric J. Ward
U.S. Geological Survey
Wetland and Aquatic Research Center
Lafayette, Louisiana, USA

Lahiru S. Wijedasa
Integrated Tropical Peat Research Program
NUS Environmental Research Institute T-Labs
National University of Singapore
Singapore
and
ConservationLinks
Singapore

Debra A. Willard
U.S. Geological Survey
Climate Research & Development Program
Reston, Virginia, USA

Lisamarie Windham-Myers
U.S. Geological Survey
Water Resources Mission Area
Menlo Park, California, USA

Victoria L. Woltz
U.S. Geological Survey
National Climate Adaptation Science Center
Reston, Virginia, USA

Isa Woo
U.S. Geological Survey
Western Ecological Research Center
Moffett Field, California, USA

Ping Yang
Key Laboratory of Humid Subtropical Eco-Geographical Process, and School of Geographical Sciences
Fujian Normal University
Fujian, China

Siyuan Ye
Key Laboratory of Coastal Wetland Biogeosciences
Qingdao Institute of Marine Geology
China Geological Survey
Shandong, China
and
Laboratory for Marine Geology
Qingdao National Laboratory for Marine Science and Technology
Shandong, China

Arturo Zaldivar-Jiménez
ATEC Asesoría Técnica y Estudios Costeros S.C.P.
Yucatán, Mexico

Zhen Zhang
Department of Geographical Sciences
University of Maryland
College Park, Maryland, USA

Zhiliang Zhu
U.S. Geological Survey
National Climate Adaptation Science Center
Reston, Virginia, USA

FOREWORD

"When I would recreate myself, I seek the darkest wood, the thickest and most impenetrable and to the citizen, most dismal, swamp. I enter a swamp as a sacred place, a sanctum sanctorum. . . I seemed to have reached a new world, so wild a place. . .far away from human society." – Henry David Thoreau, Walden and Other Writings

Thoreau's "swamp" conjures up dark images of mystery, jungle vines and wild animals, hidden far from human occupation. Today, modern society's view of wetlands is not incongruent with Thoreau's; however, we have gained an appreciation for the ecological and societal values of swamps and wetlands. These ecosystems serve as nature's water filters, storm surge buffers, and provide many other services that weren't understood in Thoreau's time.

Much has been written about the ecological function of wetlands, but to date, a comprehensive overview of wetland management incorporating carbon values has been lacking. As an ecologist and geologist that have worked extensively with both resource managers and research scientists, we have seen first-hand the need for foundational research on the processes that affect wetland functioning and focused experiments to determine how various management practices affect wetland capabilities for carbon sequestration. This is why we are delighted to write the foreword for *Wetland Carbon and Environmental Management*. This volume synthesizes work from around the globe by experienced researchers and managers in wetland-carbon management. Wetland managers, students, and academics will benefit from the authors' experiences and knowledge.

Understanding the nexus between healthy landscapes and carbon storage is the crux of this book, which provides readers an overview of management techniques with direct links to impacts on carbon sequestration. Readers will understand the complex chemical interactions that bind carbon to soil and how a healthy wetland breathes more efficiently. The culmination of the book explains how sequestering carbon, by using various management techniques, benefits wetlands by improving overall wetland function. This translates into increased ability to maximize societal and ecological benefits, such as filtering water, capturing sediment, and improving important wetland habitat.

These themes run throughout this book: reviews of the latest science on wetland carbon cycles; processes involved in wetland carbon sequestration and practices that maximize it; comparisons of the quantitative value of sequestering carbon in restored wetlands; descriptions of natural wetlands in contrast with managed or converted wetlands; and the current state of knowledge on the efficacy of restoration strategies among different wetland systems.

Using a combination of experimental and geologic studies, several chapters examine how modification of environmental factors, such as degree of flooding, changing sea level, and sediment supply, affects wetland sequestration of carbon and emission of greenhouse gases. Over long time periods, sediment and carbon accumulation rates in coastal wetlands are closely tied to natural coastal processes. For example, in the Everglades, more water equals more sequestration, but in the Sacramento delta, active flooding experiments did not mitigate soil loss. As scientists are fond of saying, "it's complicated."

Authors address tropical, coastal, inland, and northern wetland environments from around the world and include specific management recommendations for these systems. For example, subtropical mariculture ponds, converted from estuarine marsh to shrimp ponds, significantly increase carbon dioxide, methane, and nitrous oxide emissions; however, by applying simple management strategies, operators can reduce excessive greenhouse gas release. Globally, mangrove forests continue to decline. Studies in Guangxi, China, and Can Gio, Vietnam, provide new and sustained approaches to restoring mangroves with economic benefits that compensate local economies and encourage reforestation of this important ecosystem.

This book also investigates which systems store carbon most efficiently per unit basis. In other words, where do you get the biggest bang for the carbon buck? Comparisons between prairies, peatlands, marshes, and mangroves reveal interesting carbon sequestration trends with even more fascinating carbon responses, and many of the answers raise more questions for future research. Why does a prairie pothole wetland store carbon differently in a restored setting than an undisturbed site, even when all conditions appear to be similar? What makes a mangrove forest so carbon-rich compared to a freshwater marsh?

Through extensive and real-world application, *Wetland Carbon and Environmental Management* clearly identifies management responses that improve carbon sequestration while enhancing wetland health and function. The compelling evidence presented by Ken, Camille, Zhiliang, and their co-authors will strengthen the quality of wetland management and highlight areas of future research that will improve our current knowledge and understanding. We believe this book will become a primary source of information that will lead to improved techniques and practices – and help preserve Thoreau's sacred swamps around the world for the benefit and fascination of future generations.

James Scott Covington
United States Fish and Wildlife Service

Debra A. Willard
United States Geological Survey

PREFACE

The idea for this book, including its organization and contents, has its origin in the latest environmental and climate policy requirements in the United States, as well as science advances. In 2007, the U.S. Congress passed the Energy Independence and Security Act (EISA), from which Section 712 required U.S. Federal agencies to provide a better understanding of carbon and greenhouse gas fluxes across the United States. As a result, large-scale and coordinated efforts were launched to assess carbon storage, carbon fluxes, and greenhouse gas fluxes – including CO_2, CH_4, and N_2O – from all major terrestrial and freshwater aquatic ecosystems, including forest, grassland/shrub, agricultural lands, wetlands, and rivers, streams, lakes, and impoundments.

The EISA assessment produced major results (Selmants et al., 2017; Zhu, 2011; Zhu & McGuire, 2016; Zhu & Reed, 2012, 2014), but recognized that wetlands remained a significant source of uncertainty, especially for those wetlands that were being actively managed. The more recent *Second State of the Carbon Cycle Report* by the U.S. Global Change Research Program (USGCRP), which devoted two separate chapters to inland and coastal wetlands, respectively, noted that large knowledge gaps still remain, ranging from inadequate analysis of restored and managed wetlands, and consequences of management decisions, to future wetland responses to climate change (USGCRP, 2018). In recent literature, wetland management is suggested as a potential natural solution to mitigate climate change (Fargione et al., 2018, Kroeger et al., 2017) and help offset direct losses of wetlands from sea-level rise, subsidence, and coastal erosion (Wang et al., 2017). The recognition that a synthesis of wetland carbon management was urgently needed was the genesis of *Wetland Carbon and Environmental Management*; discerning the relationships between wetland management and carbon flux (loss or gain) is an international goal.

The management of wetlands to improve carbon storage, or to prevent carbon loss, is inherent to wetland stewardship. Wetland ecosystem health and sustainability, and persistence and loss, are linked to the same processes that promote carbon sequestration. Indeed, wetlands store more carbon per unit area than most other ecosystems on the planet (Nahlik & Fennessy, 2016). Wetland plant primary productivity facilitates the uptake of CO_2 from the atmosphere, and that carbon captured is committed to plant biomass both aboveground and belowground. While aboveground carbon biomass experiences different fates dependent on disturbance regime (e.g., cyclones, fire, etc.), carbon produced and stored belowground can accumulate and persist for millennia because of the presence of water, which facilitates reduced oxygen diffusion into the soil for part or most of the growing season in wetlands and decreases decomposition of organic matter. Belowground carbon is a mix of inputs from root growth and litter from senesced aboveground structures (often termed autochthonous) and that carbon combines with both inorganic and organic carbon deposited on the surface of wetlands from off-site sources (often termed allochthonous). The last few decades of dedicated research on carbon and wetlands have identified a number of links between environmental management strategies and their impacts on the biogeochemical processes such as carbon sequestration, burial, emissions, and export, and ultimately the balance of carbon in the wetland ecosystem. The management of water offers a primary tool.

Where major changes to the hydrology of wetlands have been instituted (e.g., tile draining of prairie potholes in the northern US and Canada, channeling or extracting seasonal sheet flow to drain the Everglades wetland ecosystem in Florida, leveeing large wetland areas in Europe, etc.), carbon armored by years of low oxygen diffusion into the soil is released. In addition, soil surface elevations are reduced and the naturally established long-term ecosystem balance among plant primary productivity, carbon, nutrient, and water cycling is affected permanently. More persistent flooding and reduced mineralization of nutrients further leads to reduced primary productivity, perpetuating degradation. Causes of global environmental change are less important to debate than the net effect of those changes, and locally imposed changes (e.g., cutting off tides, dumping nutrients, etc.), on preventing the wetland ecosystem from responding as it naturally would. Coastal and inland wetlands, as well as herbaceous and forested wetlands, are affected by environmental change, which also means that environmental management, if implemented properly, can potentially mitigate the additional CO_2 or CH_4 released during the degradative process.

This book synthesizes just a few wetland research studies conducted from around the world that link environmental management actions to carbon, including carbon storage, regulation of atmospheric carbon fluxes, lateral carbon transport, enhanced carbon sequestration, and improved ecosystem service value. This book is intended to explain the role that environmental management of wetlands can have in influencing carbon fluxes.

Part I presents introductory chapters that describe carbon storage on the landscape in places like the conterminous United States, detail how wetlands are involved biogeochemically, and provide an overview of some wetland management practices. This book then presents chapter-level summaries of how management influences carbon storage or loss in specific tidal wetlands (Part II) and specific non-tidal and inland wetlands (Part III). The case studies sections highlight the wide variation in how scientists assess wetland carbon processes, ranging from long-term geological studies to shorter-term flux studies, and over multiple spatial scales. All of these techniques have different applications, and while this book does not provide a comprehensive global assessment of all carbon studies underway, it provides representative accounts from multiple countries for quick reference. This book concludes with synthesis chapters (Part IV) that provide primers on the topics of carbon markets and ecosystem services, and summary results from the *Second State of the Carbon Cycle Report* delivered to the U.S. Congress in 2019 that identifies the role of inland and tidal wetlands in large-scale efforts to sequester carbon from increased atmospheric CO_2 concentrations while limiting emissions of CH_4 under certain conditions. The final chapter represents a summary of the book and identifies pathways forward.

Ken W. Krauss
Zhiliang Zhu
Camille L. Stagg
United States Geological Survey

REFERENCES

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., et al. (2018). Natural climate solutions for the United States. *Science Advances*, *4*, eaat1869. doi: 10.1126/sciadv.aat1869

Kroeger, K. D., Crooks, S., Moseman-Valtierra, S., & Tiang, J. (2017). Restoring tides to reduce methane emissions in impounded wetlands: A new and potent Blue Carbon climate change intervention. *Scientific Reports*, *7*, 11914. https://doi.org/10.1038/s41598-017-12138-4

Nahlik, A. M., & Fennessy, M.S. (2016). Carbon storage in US wetlands. *Nature Communications*, *7*, 13835. https://doi.org/10.1038/ncomms13835

Selmants, P. C., Giardina, C. P., Jacobi, J. D., & Zhu, Z. (Eds.) (2017). *Baseline and Projected Future Carbon Storage and Carbon Fluxes in Ecosystems of Hawai`i. Professional Paper 1834*. Reston, Virginia: U.S. Geological Survey.

USGCRP (2018) *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. N. Cavallaro, G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, & Z. Zhu (Eds.), U.S. Global Change Research Program, Washington, DC, USA.

Wang, H., Steyer, G. D., Couvillion, B. R., Beck, H. J., Rybczyk, J. M., Rivera-Monroy, V. H., et al. (2017). Predicting landscape effects of Mississippi River diversions on soil organic carbon sequestration. *Ecosphere*, *8*, e01984. https://doi.org/10.1002/ecs2.1984

Zhu, Z. (Ed.) (2011). *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Great Plains Region of the United States*. Professional Paper 1787. Reston, Virginia: U.S. Geological Survey.

Zhu, Z., & Reed, B. C. (Eds.) (2012). *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Western United States*. Professional Paper 1797. Reston, Virginia: U.S. Geological Survey.

Zhu, Z., & Reed, B. C. (Eds.) (2014). *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Eastern United States*. Professional Paper 1804. Reston, Virginia: U.S. Geological Survey.

Zhu, Z., & McGuire, A. D. (Eds.) (2016) *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of Alaska*. Professional Paper 1826. Reston, Virginia, USA: U.S. Geological Survey.