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Wetland Carbon and Environmental Management

Ken W. Krauss
Zhiliang Zhu
Camille L. Stagg

Editors

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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

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Part I

Introduction to Carbon Management in Wetlands

1

A Review of Global Wetland Carbon Stocks and Management Challenges

Benjamin Poulter[1], Etienne Fluet-Chouinard[2], Gustaf Hugelius[3], Charlie Koven[4], Lola Fatoyinbo[1], Susan E. Page[5], Judith A. Rosentreter[6], Lindsey S. Smart[7], Paul J. Taillie[8], Nathan Thomas[1,9], Zhen Zhang[10], and Lahiru S. Wijedasa[11,12]

ABSTRACT

Wetlands have unique soil, vegetation, and biogeochemistry that arises from their landscape position and wetland hydrology, which creates low oxygen levels in the soil. With reduced oxygen availability, plants develop adaptations to survive, such as aerenchyma, that allow transport of atmospheric oxygen to their roots, and soil microbial communities become dominated by anaerobic respiration processes that are less efficient in oxidizing carbon. Combined, the above- and belowground carbon stocks of wetlands play a key role in the global carbon cycle at varying time scales. This chapter provides a comprehensive assessment of wetland carbon stocks, research methodologies, and their historical and future trajectories. We estimate wetland carbon stocks range between 520–710 PgC (and 1792 to 1882 PgC with permafrost carbon) globally.

1.1. INTRODUCTION

1.1.1. Wetlands in the Global Carbon Cycle

Wetlands play an important role in the global carbon cycle because of the large amounts of organic carbon they store in vegetation and soils. The accumulation of

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[1] *Biospheric Sciences Laboratory, Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA*

[2] *Department of Earth System Science, Stanford University, Stanford, California, USA*

[3] *Department of Physical Geography, Stockholm University, Stockholm, Sweden; and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden*

[4] *Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*

[5] *School of Geography, Geology & the Environment, University of Leicester, Leicester, UK*

[6] *Centre for Coastal Biogeochemistry, School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW, Australia*

[7] *Center for Geospatial Analytics, North Carolina State University, Raleigh, North Carolina, USA*

[8] *Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, Florida, USA*

[9] *Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA*

[10] *Department of Geographical Sciences, University of Maryland, College Park, Maryland, USA*

[11] *Integrated Tropical Peat Research Program, NUS Environmental Research Institute, T-Labs, National University of Singapore, Singapore*

[12] *ConservationLinks, Singapore*

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carbon is partly due to the high productivity of some wetlands, such as in tropical salt marsh and mangrove ecosystems. But over long timescales, large wetland carbon stocks are found belowground, mainly because of how water-saturated soils slow rates of organic matter decomposition. Because of the large amount of carbon stored in wetlands, these ecosystems are considered to be particularly vulnerable to climate change and may act as a positive feedback to atmospheric carbon dioxide and methane concentrations as wetlands become drier or warmer, or as permafrost thaws. Estimates of global wetland carbon stocks remain uncertain due to a combination of challenges in field sampling, the scaling of site level and in-situ observations to regions, definitions and inclusivity of wetland types in different assessments, and due to year-to-year or decadal variability in wetland extent caused by human management, climate variability, and climate change. This chapter aims to provide a comprehensive assessment of global wetland carbon stock estimates, taking into account these sources of uncertainty. The chapter presents a brief overview of methods that are commonly used to estimate wetland carbon stocks, then individual sections provide estimates of stocks for key wetland types found in tropical, boreal, and temperate regions, and including those associated with "blue carbon" or coastal systems. Two additional sections on historical losses of wetlands and future trends in wetland carbon stocks are presented to provide a temporal context for carbon accounting.

According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (Ciais et al., 2013), for the period 2000–2009, global carbon stocks are distributed across the major components of the Earth system in the following reservoirs (where 1 Petagram = 1 PgC = 10^{15} gC): the atmosphere (829 PgC); the oceans (38,858 PgC, including surface, intermediate, deep sea, and dissolved organic carbon and marine biota); ocean sediments (1750 PgC); vegetation (420–620 PgC), permafrost (~1700 PgC, includes yedoma deposits); and soils (1500–2400 PgC, including litter), and with fossil fuel reserves ranging from 637–1575 PgC. Wetland soil carbon was estimated to account for 300–700 PgC (Bridgham et al., 2006), and when combined with permafrost (although with some double counting), the total wetland soil carbon stocks range from 2000–2400 PgC. While the oceans are the largest pool of carbon, most of this is not available to be exchanged with the atmosphere on decadal to centennial timescales and thus the carbon stored in vegetation and soil is more relevant when considering anthropogenic carbon-climate feedbacks. The observed 40% increase in atmospheric carbon (~240 PgC increase) from fossil fuel and land-use change activities since 1850, has led to an almost 1 °C change in global mean surface temperature, and represents a smaller order of magnitude of carbon than the combined vegetation and soil carbon pools. This means that understanding the distribution and processes responsible for global wetland carbon accumulation and oxidation is directly relevant for the climate system.

1.1.2. Wetland Definitions

Wetlands are defined by having unique hydric soils, vegetation, and hydrology due to their topographic position. Wetlands can be saltwater, freshwater, or brackish, develop carbon rich histosol soils, and host diverse aquatic adapted flora and fauna. There are many ways that the soil, vegetation, and hydrology properties can intersect with one another and this has led to a large range of wetland types and an extensive and complex nomenclature that includes more familiar categories such as "swamps," "bogs," and "marshes" to less familiar categories including "morass," "muskeg," and "carr." Here, we loosely follow the comprehensive wetland classification system established by Cowardin et al. (1979), used by many State and Federal agencies in the United States and by international treaties such as the Convention on Wetlands of International Importance (RAMSAR). The Cowardin system groups wetlands into five major systems: Marine, Estuarine, Riverine, Lacustrine, and Palustrine. In addition, the Cowardin system includes permafrost as wetlands, meaning that almost the entire Arctic region is treated as a wetland. Arguably, permafrost does not fulfil the criteria for the Cowardin wetland definition, i.e., hydrology or soil type or vegetation. Here, we distinguish between permafrost soils and high-latitude wetlands (both organic soil and mineral) aligned more closely with the classification system developed by the Canadian National Wetlands Working Group (1997). We do not provide a detailed carbon stock section for submerged reef habitats or sea grasses, and, instead, the combined estimate of Duarte (2017) is used in our summary table. We also do not provide estimates of carbon stocks in the sediments of non-vegetated, mainly Lacustrine, wetland subclasses that include rivers, lakes, and small ponds. Fig. 1.1 shows the global distribution of wetlands based on a combined remote sensing and inventory based integration, with key wetland complexes visible, such as the Hudson Bay Lowlands, the Western Siberian Lowlands, the Cuvette Central, Sudd wetlands, Okavango Delta in Africa, and the Pantanal wetlands and Amazonian lowlands in South America.

1.1.3. Overview of Chapter

The chapter is organized first by introducing methodologies used to estimate above- and belowground carbon stocks, describing field methods, remote sensing, and

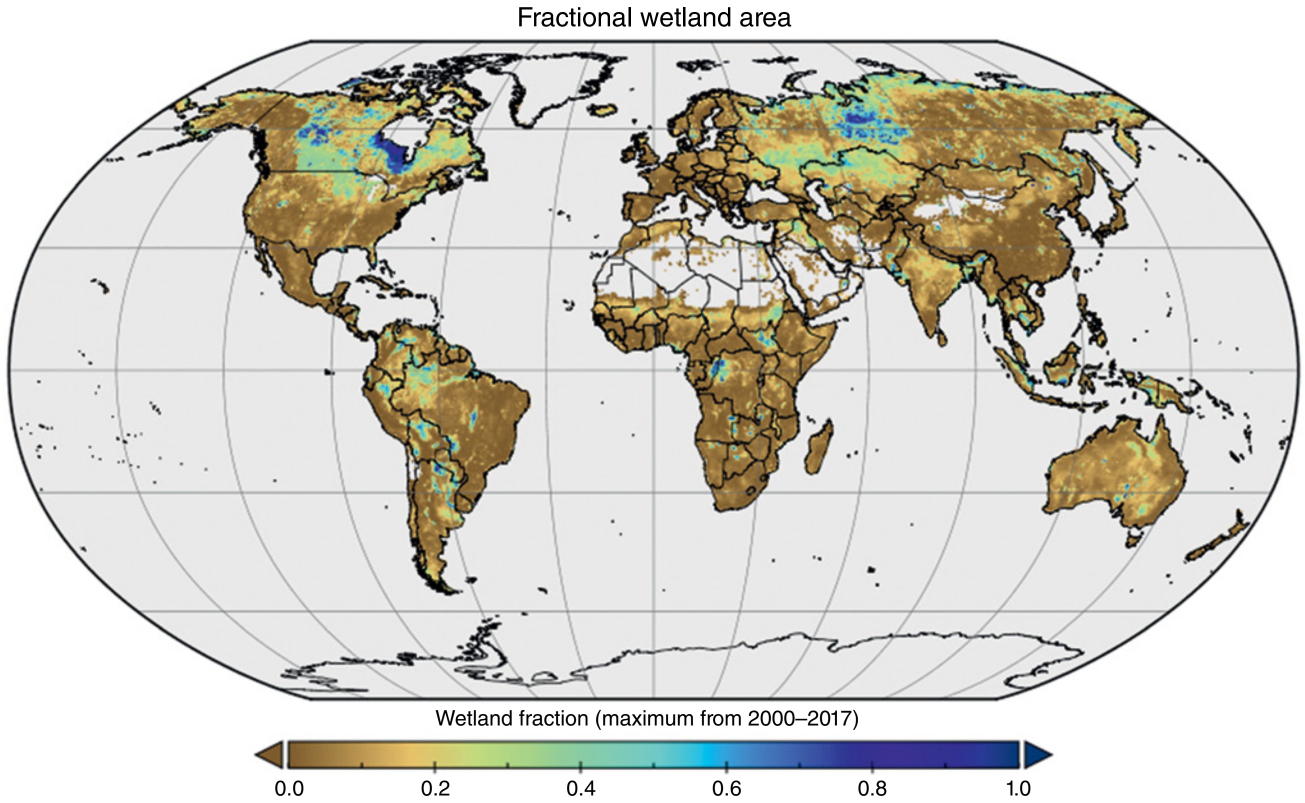

Figure 1.1 Global maximum extent of vegetated wetland area using the Wetland Area Dataset for Methane Modeling (WAD2M, based on Zhang et al., 2020), which is the basis of the wetland methane budget for Saunois et al. (2020). The dataset combines surface inundation data from the Surface Water Microwave Product Series V3.2 (SWAMPS) with inventories of tropical wetlands (Gumbricht et al., 2017), temperate wetlands (Lehner and Doll, 2004) and high-latitude wetlands (Hugelius et al., 2014). Inland waters are removed using the Landsat permanent water bodies dataset of Pekel et al. (2016) and rice cultivated areas removed using MIRCA2000.

ecological modeling approaches. A combination of these three methods is used in most regional- to global-scale accounting of carbon stocks, where field data constrain models that are used to interpret remote sensing observations of vegetation indices or soil moisture. The second section of the chapter provides a review of carbon stock estimates for boreal wetlands (permafrost and peatlands separately, and mineral soil wetlands), tropical peatlands, temperate wetlands (peatlands and mineral-soil systems), and for coastal ecosystems (mangroves and tidal marshes). The last section of the chapter describes how land-use change has affected wetlands, through drainage, degradation, and peat harvest, and more recently the conversion of tropical wetlands to oil palm plantations, and then presents how climate change is expected to affect wetland carbon stocks through increases in air temperature but also via changes in precipitation regimes.

1.2. PAST CHANGES IN WETLAND CARBON STOCKS

1.2.1. Holocene Timescale

The quantity of carbon stored in wetlands fluctuates over millennia due to climate, glacial retreat, and, more recently, from human activities that include peat extraction or drainage. Simulations of wetland extent at the Last Glacial Maximum (LGM) show wetlands were more expansive than at present, but these areal estimates remain uncertain (Kaplan, 2002; Kaplan et al., 2006). For example, larger areas of Amazonian wetlands during the mid-Holocene have been invoked as drivers of CH_4 flux to explain atmospheric CH_4 over this period (Singarayer et al., 2011). The fate of carbon in coastal wetlands submerged by the simultaneous sea level rise is less understood.

Subsequently, Holocene expansion of boreal peatlands in previously glaciated areas has sequestered significant amounts of carbon. Currently, it is thought that the catotelm in the peatlands north of 40°N alone could have accumulated 330 PgC (240–490 PgC) over the past the past 8000 years (Kleinen et al., 2012). Globally, carbon stocks in peatlands estimated from peat cores is 103 ±9 PgC and 145 ±13 PgC for the periods 11–9 kyBP and 9–7 kyBP, respectively, while earth system models estimated stocks of 54 PgC and 76 PgC for these two time periods (Stocker et al., 2014).

Historic Time Period

Carbon storage in wetlands has declined due to anthropogenic land use and land cover change, primarily from conversion to cropland, forestry, urban area, and peat extraction over the past millennia and centuries (Joosten and Clarke, 2002; Asselen et al., 2013). Artificial soil drainage also exposes soil organic carbon, accumulated over millennia, to aerobic oxidation, leading to large carbon fluxes to the atmosphere (Erb et al., 2017; Armentano, 1980). The global area of drained wetlands is estimated to be as high as 71% since 1700 (Davidson, 2014), and 35% since 1970 according to recent meta-analyses (Dixon et al., 2016; Darrah et al., 2019), while mapping approaches estimate cumulative wetland losses to be 33% (Hu et al., 2017). The uncertainty in wetland area loss presents a challenge to estimating losses in soil carbon storage.

Global inventories of land-use related emissions have not considered the impact of wetland drainage outside of recent drainage in Southeast Asia (Pongratz et al., 2018). Drainage of peat swamps in Indonesia alone are estimated to have emitted 6 PgC from 1850–2015 (Houghton and Nassikas, 2017). Peat drainage in this region still occurs at a rapid pace, i.e., 14,500 km^2 of peat swamp forest have been converted to oil palm and pulpwood plantations between 2000–2010 (Page and Hooijer, 2016). Separate accounting efforts using geospatial data and emission factors have estimated that >250,000 Mkm^2 of organic soiled wetlands were drained for agriculture globally, leading to a CO_2 release of 0.078 Pg/yr, more than one-fourth of all land-use CO_2 emissions (Tubiello et al., 2016). Nearly 13% of these emissions have occurred since 1990 (Conchedda and Tubiello, 2020). A separate bookkeeping approach estimates peatland degradation and losses to 510,000 Mkm^2 and a cumulative release of 80.8 PgC (Leifeld and Menichetti, 2018). Following drainage, carbon is likely also transported to the river network then to the ocean as dissolved carbon, though this pathway and emissions of carbon to the atmosphere is uncertain (Cole et al., 2007). The decline in global wetland area since 1850 is estimated to have reduced methane emissions by 56 Tg CH_4/yr with most of the decline from the northern temperate zone (Paudel et al., 2016).

1.3. METHODOLOGIES

1.3.1. Field Sampling of Wetland Carbon Stocks

Monitoring wetland vegetation and carbon stocks remotely via satellites and airborne instruments is increasingly common, but field-based monitoring remains fundamental to understanding and quantifying wetland characteristics. Several important biogeochemical pathways unique to wetlands form important links between wetland vegetation, water, and soil (Ardón et al., 2013; Herbert et al., 2015; Osland et al., 2016). Therefore, monitoring both vegetation and soil over time are requisite to more comprehensively understanding wetland responses to global change (Taillie et al., 2019).

Both the vegetation composition and ecosystem structure contribute to the ecological function and value of wetlands. Though wetlands are often characterized according to the dominant plant species (e.g., "pond pine pocosin"), threshold responses to stressors can make certain species indicators for given stressors (Dufrêne & Legendre, 1997). As such, inventory of canopy species, as well as herbaceous and woody groundcover, may be necessary to adequately describe wetlands, particularly in temperate regions (Bratton, 1976). Aside from species composition, variation in vegetation structure (e.g., height, density, heterogeneity) may be dramatically different within and among wetlands. In addition, some variation in vegetation structure, such as mid- and under-story vegetation density, may be difficult to estimate via remote sensing and will be best quantified via field-based inventory (Riegel et al., 2013). Given the effort required to survey plants within a plot, care should be taken to balance the number and size of experimental units that are appropriate for the research objectives and capturing landscape heterogeneity. In forested settings, 11-m radius plots are often used (Henttonen & Kangas, 2015). Selecting in-situ measurements to match the scale of observation of airborne and spaceborne remotely sensed data (e.g., canopy height) may allow for scaling up field-collected measurements (Hudak et al., 2012; Riegel et al., 2013).

Because of the value of wetlands for carbon storage, researchers often aim to translate vegetation inventories to biomass or carbon stocks. Such calculations are often made with the use of allometric equations which estimate the volume or biomass stored in an individual plant based on the species and either height or diameter-at-breast-height, DBH (Jenkins et al., 2004). Canopy height, and various derived metrics, are often measured to verify models based on remote sensing, but field measurement with a clinometer can be time intensive and logistically impractical when vegetation is dense. Regardless, documented relationships between DBH and height for a given species can be used to extrapolate aboveground biomass to large spatial extent if canopy height and species composition are available via remote sensing (Smart et al., 2020). Though more commonly employed in forested settings, this method may also be used in herbaceous wetlands (Trilla et al., 2009).

Field sampling of soil characteristics, such as the depth of the organic profile, bulk density and its vertical profile, and chemical composition, is particularly important for estimating belowground carbon stocks. Specifically, the quantity and quality of soil pore water drive carbon accumulation and long-term storage. For example, salinity is among the dominant drivers of vegetation change in coastal wetlands (Taillie et al., 2019; Williams et al., 1999), while hydroperiod holds this role in inland wetlands (Ross et al., 2003). While more sophisticated soil sampling may reveal changes with depth, a crude sample collected with a small shovel and a Mehlich III extraction is often sufficient to determine salinity, cation exchange capacity, and the ratio of organic to mineral soil (Taillie et al., 2019). In wetlands with standing water, contamination with surface water is inevitable, and thus is susceptible to daily fluctuation in salinity as a function of precipitation, evapotranspiration, and other water processes (Herbert et al., 2015). As such, coastal wetlands should be sampled during both dry and wet periods to best understand the variation in salinity as a function of precipitation and salinization (Herbert et al., 2015). Though evidence of salinization may persist longer in soils compared to surface waters (Chagué-Goff et al., 2012), soil cation concentrations may not accurately reflect the history of saltwater exposure over multiple years.

1.3.2. Remote Sensing

Spaceborne observations of the land surface provide reflectance information that is related to ecosystem optical and emissivity properties. Optical remote sensing typically measures surface reflectance in wavelengths ranging from ultraviolet to the longwave-infrared regions, whereas microwave observations (including active and passive approaches) use longer wavelengths to observe brightness temperature (as it relates to soil moisture), and active LIDAR records light travel time that is related to how ecosystem structure modifies the profile of a laser beam return. Remote sensing per se does not measure above- or belowground structure directly; for example, the surface retrievals, referred to as Level 2 products, include the atmospherically and geometrically corrected surface information, but require the application of algorithms to derive vegetation or soil properties (i.e., Level 3 products) or models to produce process-level information (i.e., Level 4 products).

In this context, remote sensing observations can provide spatially consistent information on ecosystem type and composition as well as ecosystem structure (i.e., via canopy height models), both of which can be used to derive information on above- and below ground carbon stocks. The use of remote-sensing derived information also requires knowledge on how to integrate temporal revisit as well as ground sampling distance (GSD), or spatial resolution, which can introduce uncertainties in terms of detection of seasonally flooded wetlands, or introduce "double counting" of wetlands when using coarse spatial resolution data (>500 m).

Some examples of how remote sensing has informed wetland carbon stock accounting are included in this chapter; for example, where remote sensing data based on the MODIS sensor aboard AQUA and TERRA has been used to map vegetation indices linked to wetland habitat. Or where passive and active microwave observations (i.e., NASA's AMSR and SMAP missions) have been used to derive permafrost and soil moisture information used in ecosystem models. And where radar and lidar information from the German Aerospace Center (DLR) mission Tandem-X and airborne instruments (e.g., NASA's G-LiHT, ECOSAR) have been used to map canopy height and to relate this to biomass models to estimate aboveground carbon stocks. Advances in remote sensing, particularly in improved spatial resolution capabilities, will contribute to better delineation of wetland types using high-resolution optical data (see Cooley et al., 2019) and for determining aboveground structure of vegetation in the case of the International Space Station (ISS) small-footprint waveform lidar mission "GEDI." In addition, operational and emerging hyperspectral remote sensing missions such as on the ISS like the DLR Earth Sensing Imaging Spectrometer (DESIS), and "free flying" spacecraft proposed by the European Space Agency CHIME and NASA Surface Biology and Geology (SBG) missions, have potential to use more sophisticated algorithms relating surface reflectance to soil carbon content.

1.3.3. Ecosystem Modeling

Modeling approaches used to estimate above- and belowground stocks of wetland carbon can be partitioned to diagnostic and prognostic approaches. Diagnostic modeling tends to rely more heavily on observational data, such as remote-sensing derived vegetation distributions, to initialize and update model states over time. In contrast, prognostic modeling relies on "first principles," where fundamental relationships linking biophysical information, carbon uptake, carbon allocation, and carbon turnover determine vegetation and soil carbon stocks. Many examples of diagnostic and prognostic wetland modeling comparisons exist in the literature and the uncertainties between and among these approaches remains high (Fisher et al., 2015).

To some extent, all the estimates of above- and belowground carbon stocks require empirical or process-based models either to scale site-level measurement, or convert volumetric to mass-based estimates, or to attribute changes over time due to climate and land use. However, the relationship of the models to underlying data reflects a gradient of data-constrained to process-based representation of how estimates are made. The estimates provided in this chapter span this gradient, with some emphasizing empirical approaches, where carbon density is multiplied by wetland area, others using semi-empirical methods, where the carbon densities are spatially constrained by remote sensing observations, or where prognostic models are used to assess long-term historical or future climate feedbacks on carbon turnover and respiration losses.

1.4. ESTIMATES OF WETLAND STOCKS BY WETLAND TYPES

1.4.1. Mangroves

Mangroves and other tidal wetlands have the highest carbon density among terrestrial ecosystems (McLeod et al., 2011). Although they only represent 0.3% of the total forest area (or 0.1 % of land area), C emissions from mangrove destruction alone at current rates could be equivalent to up to 1–10% of carbon emissions from deforestation (Donato et al., 2011; Richards et al., 2020). From 1996 to 2016, 158.4 Mt of C (1.8%) was lost from mangrove ecosystems (Richards et al., 2020), with total emissions per year ranging from 25–29 Tg CO_2-equivalent (Friess, 2019). Due to their location along highly populated coastlines, they are under significant threat from anthropogenic activity as well as sea level rise and climate extremes. In fact, it is estimated that over 50% of mangrove forests and tidal marshes have been destroyed over the past 60 years, at a rate of 1% to 2%/yr (McLeod et al., 2011), although contemporary (2000–2016) rates of loss have reduced (0.13%/yr), particularly from anthropogenic destruction (Goldberg et al., 2020). The high C sequestration coupled with the high risk of future destruction makes mangroves a prime candidate for carbon mitigation initiatives such as the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Degradation in Developing Countries (UNREDD and REDD+).

One of the main challenges to implementing carbon mitigation projects is measuring carbon efficiently, effectively, and safely. In mangroves especially, the extreme difficulty of the terrain has hindered the establishment of sufficient field plots needed to accurately measure carbon on the scale necessary to relate remotely sensed measurements with field measurements at accuracies of 80 to 90% as required for REDD and other carbon trading mechanisms (UNREDD, 2010). Furthermore, most intensive mangrove sites are established in South-East Asia, Australia, and Latin America, with a large gap in knowledge in African mangrove ecosystems.

Mangrove aboveground biomass (AGB) and aboveground carbon (AGC) are strongly related to mangrove height, thus the largest AGC estimates are found among the world's tallest stands. Mangrove height is driven by temperature and precipitation and so the largest forests are found close to the equator, with notably large stands on the west coast of Colombia and in Gabon, where the world's tallest stands of 63 m are found (Simard et al., 2019). Shorter trees are found towards the extremes of their geographic limits, such as in higher-latitude countries like Japan and New Zealand. However, the maximum height that mangroves are able to achieve is often limited by the occurrence of tropical cyclones and hurricanes (Simard et al., 2019). These extreme weather events limit the height of mangroves in regions where taller mangrove forests would be expected, such as in equatorial East Africa. Mangrove forest height is determined by a number of local scale variables which include salinity, hydraulic conductivity, wave exposure, and soil type, which lead to local and regional variation in height and AGC.

At national and regional levels, total mangrove carbon stocks are also driven by mangrove areal extent. Asia contains 40% of the total global mangrove area, therefore it contains over half (52%) of the total global mangrove AGB. Indonesia alone contains 22% of the global mangrove AGC stock, due to its vast mangrove area and mean mangrove AGB of 215 Mg/ha. The total AGB in mangrove forests globally is estimated at 1.52 (Hu et al., 2020) to 1.75 PgC (Simard et al., 2019), with 20.7% stored in Africa, 11.9% in Oceania, 39.3% in Asia, 27.9% in the Americas, and 0.2% stored in the Middle East. The total mangrove ecosystem carbon, however, is dominated by that which is stored in the soils. The soil C alone has been estimated to range from 1.93 PgC (Ouyang & Lee, 2019) to 6.4 PgC (Sanderman et al., 2018), although the overlap of uncertainty between these estimates is approximately equal. Lower estimates of mangrove soil carbon tend to be more common, from 1.93 to 2.96 PgC (Ouyang & Lee, 2019; Hamilton & Friess, 2018). Africa stores 13–19% of the soil C to 1 m depth with 28% stored in the Americas, 10% stored in Oceania, 42–49% stored in Asia, and no more than 0.2% in the Middle East. The controls on this total soil C are driven by coastal environmental settings (such as Holocene sea level rise and current tidal regimes), which can be divided into classes of deltas (river dominated), estuaries (tide dominated), lagoons (wave dominated), composite (river and wave dominated),