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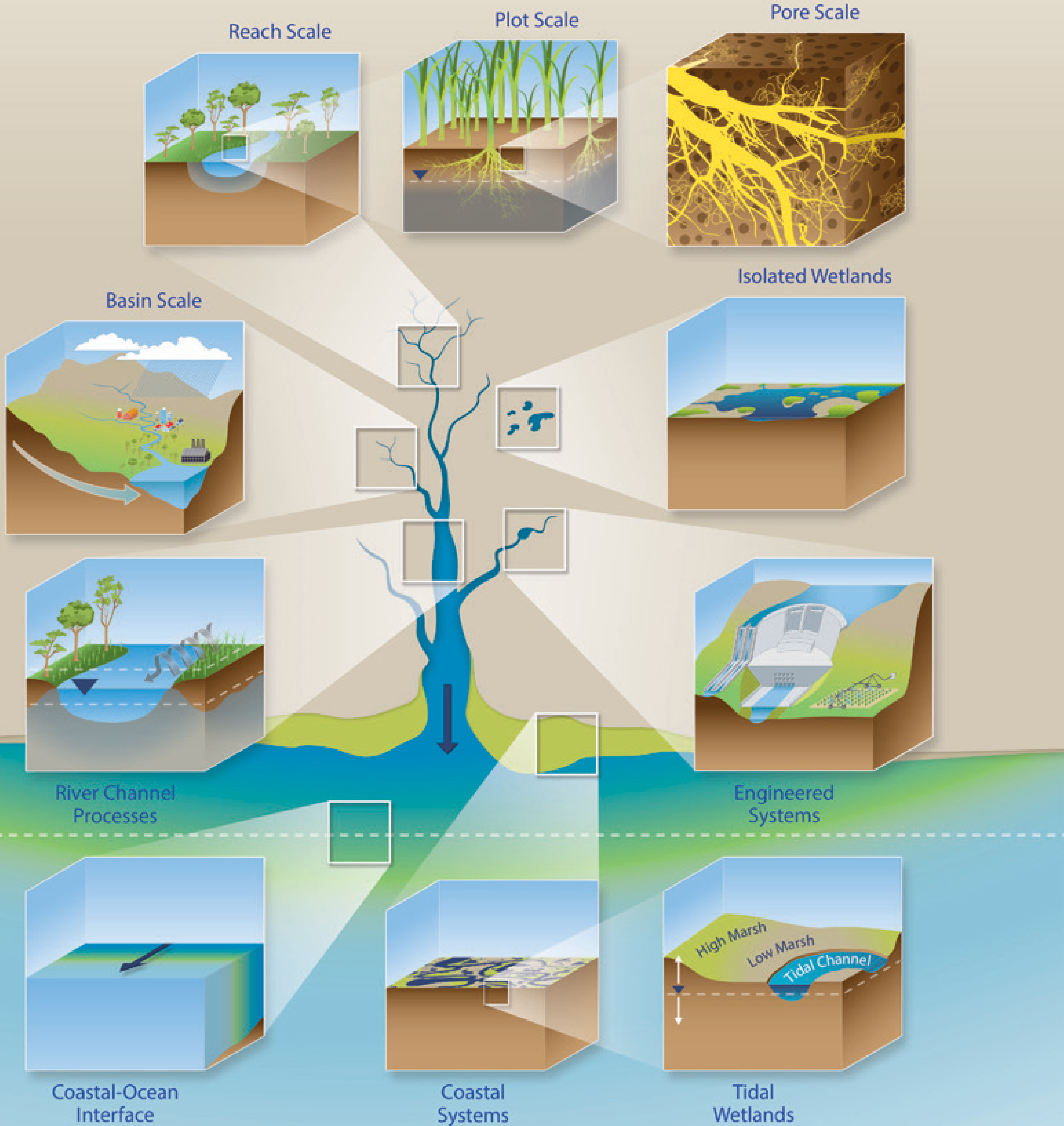
Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models

Workshop Report



U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Biological and Environmental Research

Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop

September 7–9, 2016

Convened by
U.S. Department of Energy
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Office of Biological and Environmental Research

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Mission

The Office of Biological and Environmental Research (BER) advances world-class fundamental research programs and scientific user facilities to support the Department of Energy's energy, environment, and basic research missions. Addressing diverse and critical global challenges, the BER program seeks to understand how genomic information is translated to functional capabilities, enabling more confident redesign of microbes and plants for sustainable biofuel production, improved carbon storage, or contaminant bioremediation. BER research advances understanding of the roles of Earth's biogeochemical systems (the atmosphere, land, oceans, sea ice, and subsurface) in determining climate so that it can be predicted decades or centuries into the future, information needed to plan for future energy and resource needs. Solutions to these challenges are driven by a foundation of scientific knowledge and inquiry in atmospheric chemistry and physics, ecology, biology, and biogeochemisty.

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Preface and Acknowledgements

The terrestrial-aquatic interface (TAI) is a highly dynamic component of the Earth system, developed from a near balance between terrestrial and aquatic conditions and forming unique processes and community assemblages. Furthermore, TAIs are known to play a critical role in carbon biogeochemical cycling and have the potential to provide major feedbacks to the Earth system (e.g., methane production). However, there is a lack of basic data and multiscale models to adequately describe how a changing climate can influence the key processes (also an unknown) related to Earth system–relevant feedbacks in these unique, ubiquitous ecosystems.

In general, Earth system models (ESMs) have excluded TAI ecosystem processes, thus creating tremendous uncertainty as to how TAIs will influence climate feedbacks across a range of scales, spanning from local to global. For example, ESMs represent wetlands very simplistically at best (e.g., the Accelerated Climate Modeling for Energy project) and include only a static fraction of dry land or open water, entirely lacking key processes in these hybrid areas and critical climate and biological feedbacks between land and water. This new area of research, therefore, must integrate a variety of important research topics—plants, soil, hydrology, reactive transport, microbiology, genomics, and modeling—into a systems-level understanding that can be extended to improve predictive modeling capabilities.

The goal of the September 2016 Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop was to engage the scientific community in an open discussion about critical scientific gaps. These gaps and research topics demand immediate field investigations to gather data for representing these important, yet understudied and underrepresented, ecosystems in ESMs. Workshop results will inform the U.S. Department of Energy's Office of Biological and Environmental Research (BER) as it plans and prepares for future research efforts that address the TAI gap through model-informed and model-inspired field studies. The resulting data will enable iterative refinement of high-resolution, next-generation ESMs. Specifically, the workshop (1) summarized past and current field, process, and modeling TAI research; (2) identified critical sensitivities and uncertainties in the systems; (3) identified key processes, traits, existing data, and environmental variables needed to adequately characterize these systems; and (4) discussed idealized strategies that couple models and experiments to advance the state of the science in TAI modeling, including potential experiments that would test and improve land model fidelity.

Given the integrative nature of TAIs, the success of future research efforts necessitates the coordination and collaboration of numerous federal agencies based on their particular expertise and mission. This workshop defined TAIs by a set of common processes that dramatically influence the Earth system, encompassing both coastal ecosystems (e.g., salt marshes and mangrove forests) and inland wetland ecosystems (e.g., peatlands, floodplains, and wet meadows). Common traits among all these ecosystems are that they are carbon rich; have great potential for carbon dioxide and methane flux; are globally ubiquitous; and are sensitive to climate changes through rising sea level, altered water table, and drought. The workshop did not

consider TAIs that are weighted heavily as aquatic (e.g., open water systems, seagrass meadows, or mud flats).

BER appreciates the tireless efforts of the workshop organizers, co-writers, and contributors who vigorously participated in workshop discussions and generously gave their time and ideas to this important activity. The workshop would not have been possible without the scientific vision and leadership of its organizing committee. BER also extends special thanks to the speakers who gave thought-provoking presentations: Vanessa Bailey, Scott Fendorf, Ruby Leung, William McDowell, Patrick Megonigal, Peter Raymond, Joel Rowland, Tiffany Troxler, and Kelly Wrighton. In addition, session rapporteurs deserve acknowledgement for capturing the ideas discussed in breakout sessions for use in the creation of this report: Ben Bond-Lamberty, Elizabeth Canuel, Ethan Coon, Heida Diefenderfer, Scott Fendorf, Adam Langley, Melanie Mayes, Rebecca Newcomer, Peter Raymond, and Peter Thornton. Lastly, BER lauds the efforts of the workshop writing team who created this document: Vanessa Bailey, Brian Benscoter, Ben Bond-Lamberty, Elizabeth Canuel, Ethan Coon, Heida Diefenderfer, Scott Fendorf, Adam Langley, Patrick Megonigal, Peter Raymond, Joel Rowland, James Stegen, Peter Thornton, and Tiffany Troxler.

Also acknowledged are the outstanding efforts of the staff from Oak Ridge National Laboratory's Biological and Environmental Research Information System, who helped create the workshop visuals and edited and prepared this report for publication.

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Executive Summary

What are Terrestrial-Aquatic Interfaces?

Terrestrial-aquatic interfaces (TAIs) are dynamic and complex components of the Earth system that are transitional between fully terrestrial and fully aquatic environments. They possess unique biological, hydrological, and biogeochemical attributes that produce exceptionally high rates of biological productivity and biogeochemical cycling. These TAIs regulate the Earth system at a level that far exceeds the area they occupy. They capture, store, transform, and release carbon, nitrogen, phosphorus, sediments, water, and energy, thereby participating in Earth system cycles that ultimately feed back on the atmosphere, climate, and aquatic ecosystems. Recent developments clearly indicate that a comprehensive understanding of the Earth system is possible only with a detailed understanding of the phenomena that occur where terrestrial and aquatic ecosystems meet (see sidebar, Terrestrial-Aquatic Interface Dynamics, this page).

The past decade witnessed significant advances in understanding the role that Earth biomes play in regulating the Earth system. New Earth system research in terrestrial biomes includes studies in tropical forests, temperate forests, boreal peatlands, and Arctic landscapes. Knowledge of the local, regional, and global carbon budgets of aquatic ecosystems (e.g., rivers, lakes, estuaries, and oceans) has improved significantly, enabling new understanding of the important role these components play in the global carbon cycle. However, research efforts in terrestrial and aquatic systems have been largely independent of one another, championed by separate communities of scientists and agencies. Generally, Earth system research focused on TAIs has been the purview of groups who specialize in ecosystems such as wetlands that typically form at such interfaces. These separate efforts have converged on the conclusion that TAI systems are global "hot spots" of biological, biogeochemical, and ecological activities that are critical to the planet-wide Earth system. The next frontier in developing a holistic

Terrestrial-Aquatic Interface Dynamics—A Large Source of Uncertainty in Modeling

The critically important terrestrial-aquatic interface is not characterized by geographic location or ecosystem type; rather, it is defined by physical interactions that drive keystone processes. This interface is not merely a conduit for the exchange of soluble and particulate materials between soils and water bodies; it is biogeochemically and hydrologically dynamic, transforming the materials that flow through the system.

Because steep process gradients in spatially compressed zones characterize these interfaces, there is insufficient understanding of these process dynamics, which often are inferred only by comparing measurements of fluxes into and out of the interfaces. This limited knowledge is a large source of uncertainty in global and regional carbon, environmental, and climate models, significantly impeding the ability to couple models across traditional process and research domains in meaningful and robust ways.

understanding of Earth surface processes is to explicitly couple the dynamics of terrestrial and aquatic systems at their interface. This challenge is daunting because of the many unique processes that arise in TAIs.

Terrestrial-aquatic interfaces often are classified as wetlands, marshes, mangroves, swamps, peatlands, floodplains, riparian zones, hyporheic zones, lake margins, groundwater seeps, and similar transitional areas. However, such designations fail to articulate the unique traits that make TAIs important features of the Earth system. Indeed, the characteristic processes controlling their formation and functioning best define TAIs. These interfaces support unique biological communities, rapid rates of biological productivity, and microbial activity. Although TAIs are limited locally in areal extent, they collectively form a spatially extensive global network that regulates the planet's biogeochemical cycles.

These systems exhibit high temporal and spatial variation in oxygen supply, have carbon-rich soils, are high potential greenhouse gas emitters, and are sensitive to anthropogenic disturbances (e.g., pollution and fire) and climate change impacts. One useful consequence of defining TAIs by the processes they support is that the boundaries between systems are realistically vague and dependent on the distribution of relevant processes of interest. From a terrestrial perspective, the distribution of processes may be steepest near the physical boundary between domains, diminishing rapidly into the aquatic realm but attenuating gradually over large distances into the terrestrial realm. The reverse perspective is likely for research interests that lie predominantly in estuaries, large rivers, and open water. Defining TAIs in this way encourages the development of observational and modeling approaches that span these upland-aquatic transitions, while remaining faithful to the process representations required within purely aquatic and terrestrial systems.

Why are Terrestrial-Aquatic Interface Systems Unique and Important?

Perhaps the most important feature of TAI systems from an Earth science perspective is their role as hot spots and "hot moments" of biogeochemical activity. Examples of processes that peak in TAIs include net primary production, net ecosystem production, denitrification, sediment deposition, export of organic and inorganic carbon, and emissions of greenhouse gases.

Terrestrial-aquatic interface systems affect global cycles more prominently than expected based on the proportion of the land surface they occupy because TAIs support exceptionally high rates of Earth system and environmental processes.

Hydrology is a key feature of TAIs, in part, because water is an effective barrier to oxygen diffusion and creates a sharp boundary separating areas dominated by aerobic versus anaerobic microbial activity. Gradients in oxygen availability are relevant at scales ranging from soil pore spaces to landscapes. The anaerobic microsites of fully terrestrial (upland) soils rapidly transition into an anaerobic matrix across a water-saturated boundary, whether it be the water table surface in a soil profile or an upland-to-wetland transition along an elevation gradient. In places where water regularly rises to the soil surface, there are distinctive vegetation communities dominated by plant species that tolerate anaerobic conditions. In TAIs, organic carbon, oxygen, and nutrients required by plants and microbes for growth and respiration come from the terrestrial or aquatic systems adjacent to groundwater and surface water and from *in situ* production by plants and microorganisms in the TAI itself.

Elements, compounds, and matter that originate in terrestrial systems are dramatically transformed in TAIs before they emerge in adjacent aquatic systems. The nature of these transformations is controlled by the hydrologic flow path across TAIs and the traits of plant, animal, and microbial species that dominate these interfaces. Plants and microorganisms in TAIs add elements, compounds, and particulate matter directly into adjacent aquatic ecosystems via water discharge. Thus, TAIs exert an overwhelming influence on the biogeochemistry and ecology of aquatic ecosystems.

Dynamic change, or the potential for change, is a common feature to most TAIs. Consequently, TAIs differ from other ecosystem types in that relatively subtle changes in their boundary conditions can affect the very existence and spatial location of TAIs. There is a high potential for state change or ecosystem collapse with minor changes to vegetation or surface properties. For instance, many tidal wetlands build soil vertically by trapping exogenous and *in situ* sediment, thus gaining elevation with sea level rise, and the perturbations to sediment supply can convert the wetlands to mud flats or open water. Dramatic state changes often are irreversible on a human time scale and have enormous consequences for biogeochemical cycles. TAIs are particularly vulnerable to the pressures of climate and environmental changes such as those in precipitation patterns, sea level rise, increasing salinity, and the frequency of extreme events. These events that are known to influence TAIs include short-term, pulse-type disturbances such as fire and storm surges and the more persistent, press-type events such as drought, altered plant species composition, and groundwater extraction. Therefore, a robust understanding of TAIs requires a focus on their dynamic properties that are most sensitive to change, specifically the hydrologic continuum between terrestrial and aquatic ecosystems, accompanying reduction-oxidation and transport processes, and plant-microbe community ecology.

Scale is an inherent property of natural systems that poses special challenges in TAIs. Conceptually, TAIs and their distinctive processes exist across vast spatial (and temporal) scales, ranging from micrometer-scale oxygen gradients in soil aggregates to kilometer-scale transitions in ecosystems across elevation gradients. Overlain on the spatial scale is shape; TAIs at all scales typically are irregularly shaped features that are difficult to observe, quantify, and model. Scaling processes within a specific type of ecosystem is a challenge, but far more challenging is coupling terrestrial and aquatic systems because each operates at distinctly different temporal and spatial scales. The multiscale nature of temporal and spatial gradients across interfaces represents one of the greatest challenges in Earth system research—one that requires the integration of physics, hydrology, biogeochemistry, biology, and Earth system feedbacks.

What is the State of Knowledge at the Terrestrial-Aquatic Interface?

The U.S. Department of Energy's Office of Biological and Environmental Research (BER) held the Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop in Washington, D.C., on September 7–9, 2016. BER sponsored the workshop for scientists who study terrestrial, aquatic, and TAI systems to assess the state of the science in coupled terrestrial and aquatic ecosystems and to develop a strategy for advancing Earth system research at the TAI. The assembled group agreed that there is a lack of observational data and models required to adequately understand the key ecological, biogeochemical, hydrological, and physical processes that interact in TAIs and feed back on the Earth system. Also recognized were that terrestrial, TAI, and aquatic systems each operate with fundamentally different temporal and spatial dynamics and that coupling across such systems will require conceptual advances, new observations, coordinated experimental efforts, new modeling frameworks, and transdisciplinary research teams.

Existing observations and models of surface and subsurface hydrology, biogeochemistry, plant ecology, and microbial ecology fail to address key knowledge gaps unique to TAIs. Gaps often are related to the fact that processes operate at fundamentally different temporal and spatial scales in terrestrial systems compared to those in the aquatic ecosystems to which they are coupled. There is limited understanding to inform decisions about scaling up a system response such as methane (CH_4) emissions—when to use an empirical approach versus process-based numerical models. Identifying the need for upscaling and developing the appropriate methodologies to achieve it are essential for incorporating knowledge gained from multiscale experiments into predictive multiscale models. An inability to predict such scale transitions may indicate structural deficiencies in the models themselves. In that case, new experiment-model iterations would be needed to elucidate processes that cause observed scale dependencies.

Advances in TAI science will require a creative combination of experimental manipulations, cross-system observations, and multiscale numerical and statistical models. Research in this field can advance quickly by integrating models and empirical science into a comprehensive program designed to (1) provide empirical constraints (likely varying across systems) to calibrate and evaluate models and (2) reveal mechanisms needing improvements in process-based predictive models.

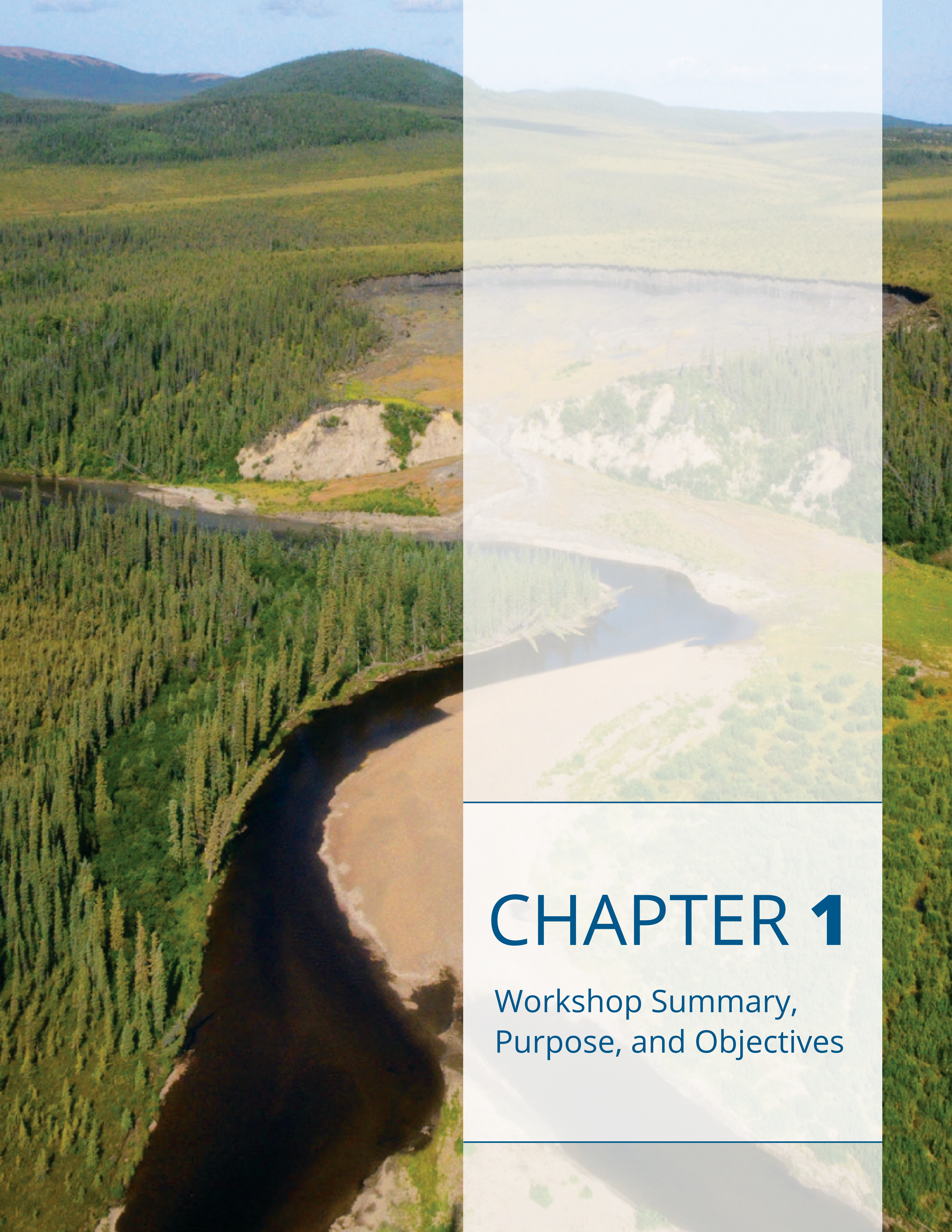
Key Gaps and Research Recommendations for Terrestrial-Aquatic Interface Science

Because TAIs are globally ubiquitous, achieving a fundamental understanding of the hallmark processes in these systems requires extending system-specific observations to a globally relevant knowledgebase and, for the first time, coupled terrestrial, aquatic, and TAI models. Ignoring these critical interfaces clearly limits the ability to couple the largest features of the Earth system—land, water, and ocean—to achieve a fully comprehensive understanding of the global system. Workshop participants identified several research challenges to focus these efforts:

- The size and shape of TAIs have prevented an accurate accounting of their locations, areal extent, species composition, and basic ecosystem inventories such as carbon and nutrient pools. An exact accounting of stocks, fluxes, and transformations in TAIs is a fundamental need that requires accurate, high-resolution maps and digital elevation models. Such information continues to elude TAI scientists but is needed before spatial models can represent TAI processes.
- Hydrology is a fundamental control on biological, biogeochemical, and geomorphological processes in ecosystems. Hydrologic observations and models tend to focus on specific types of systems such as terrestrial ecosystems, rivers, estuaries, or groundwater. Advancing TAI science requires cross-system hydrologic observations and models that explicitly account for interactions between surface and groundwater as the water moves through TAI plant communities and soils.
- Plants exert a second level of fundamental control on biological, biogeochemical, and geomorphological processes in TAIs. Plant species in TAIs share highly specialized traits for tolerating anaerobic conditions, flooding, salinity, sediment deposition, and other sources of stress. Although the physiological and morphological bases of such traits are well understood, their response to factors such as elevated carbon dioxide (CO_2) or changes in hydrology or environment is generally not well known. Thus, these traits and responses are poorly represented in models of any kind including environmental and Earth system models. This limited understanding of the responses of specialized plant traits to global change is a gap in TAI science.
- Microorganisms interact with plants and plant-derived or plant-transported substrates to cycle carbon, nutrients, and pollutants in TAIs. The juxtaposition of aerobic and anaerobic conditions that exist at the interface supports rapid rates of microbial activity and uniquely coupled processes. Because plants are sources of organic carbon (e.g., energy) and respiratory substrates (e.g., oxygen) and are conduits for emitting greenhouse gases (e.g., CO_2 and CH_4), these systems cannot be understood without mechanistic knowledge of microbe-plant interactions. Microbial processes in the plant rhizosphere represent significant uncertainty and a knowledge gap in the understanding of TAIs. Understanding these processes is essential for inclusion in models.

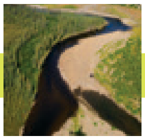
- TAI systems are highly dynamic features that move, expand, or contract at time scales of hours to years. Changes can occur in both the vertical and horizontal dimensions and be driven by changing hydrology, sediment supply, plant community composition, or chemical inputs in high-frequency or short-frequency events. Current observations, experiments, and models do not account for interactions among plant processes, soil processes, and hydrologic processes that drive geomorphic changes across terrestrial to aquatic ecosystem interfaces and boundaries.
- TAIs are an extreme example of the more general scientific and computational problems surrounding scale. Processes operating at small scales of time and space in TAIs drive large-scale phenomena that cannot be predicted with existing observational or modeling techniques. Scale also presents a challenge when coupling models that were designed to operate as isolated units because terrestrial, TAI, and aquatic systems operate at distinctly different temporal and spatial scales. Advancing TAI science requires creative approaches to combining experiments, models, and observations in ways that respect (rather than ignore) these inherent differences in scale.
- Highly responsive to perturbations, TAIs are prone to sudden changes in function or wholesale changes in state (e.g., from wetland to aquatic). Internal TAI processes operating at small scales respond to large-scale external events such as sea level rise, drought, and flooding. Scale-relevant research is needed to predict the impacts of these perturbations on the interface's relatively narrow zone. A particular challenge will be to forecast how TAI ecosystems (and the terrestrial or aquatic systems to which they are coupled) respond to forcing from external drivers such as changes in climate, environment, and land use. Forecasting changes in function and state requires a more detailed understanding than now exists of the feedbacks inherent in TAI systems that render them resilient to perturbations.

Clearly, human systems need consideration in any study of TAI ecosystems because of the immensity of their effects on key physical and biological processes. Meeting this goal will require the participation of multiple TAI stakeholders including the National Oceanic and Atmospheric Administration, U.S. Geological Survey, U.S. Department of Agriculture, Smithsonian Institution, National Science Foundation, and National Aeronautics and Space Administration. The need for a TAI-focused research program arises from the fact that critical Earth and environmental system processes cross the traditional terrestrial-TAI-aquatic boundaries adopted by funding agencies. As a result, integrated and coordinated research is needed at the terrestrial-aquatic interface to be fully successful.



CHAPTER 1

Workshop Summary, Purpose, and Objectives



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Workshop Summary, Purpose, and Objectives

Terrestrial-aquatic interfaces (TAIs) are highly dynamic components of Earth and environmental systems that lie in the complex transition zone between terrestrial and aquatic conditions. TAIs are ecosystems with unique plant traits, microbial communities, hydrology, geomorphology, and biogeochemical processes, but these interfaces also are coupled intimately to biological, physical, and chemical processes occurring in adjacent terrestrial and aquatic ecosystems. TAIs play a critical role in carbon, nutrient, and contaminant biogeochemical cycling, and they feed back on Earth and environmental systems through the storage, transformation, and release of elements (i.e., carbon and nitrogen) involved in the production, export, and emission of greenhouse gases such as carbon dioxide, methane, and nitrous oxide. TAI systems also can have a dominant influence on the biology and chemistry of downstream aquatic ecosystems and their interactions with the atmosphere.

Advances over the past 2 decades have clearly shown that TAI systems are important in local, regional, and global biogeochemical cycles and that TAI processes must be considered to understand and model the coupling between terrestrial and aquatic ecosystems. Supported by various funding agencies, research programs have made progress by focusing on independent studies of terrestrial, TAI, or aquatic systems. The emerging general consensus is that further progress at improving understanding of the Earth system will require new efforts that explicitly cross these traditional disciplinary boundaries (see Appendix 1: Federal Interagency Coordination and Collaboration, p. 63). However, there is a lack of basic data and multiscale models to adequately describe and represent how these unique and ubiquitous ecosystems influence Earth system processes. Thus, most Earth system models (ESMs) exclude TAI processes. For example, ESMs incorporate wetlands with very simplistic hydrological, biogeochemical, and plant representations but lack the dynamic feedbacks that capture changes in spatial distribution over seasons or years. This new area of research, therefore, must integrate a variety of important research areas—plant and microbial ecology, soil science, hydrology, reactive transport, microbiology, genomics, and modeling—into a robust systems-level understanding that improves predictive modeling capabilities.

The U.S. Department of Energy's (DOE) Office of Biological and Environmental Research (BER) held the Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop in Washington, D.C., on September 7–9, 2016 (see Appendix 2: Agenda, p. 65). BER sponsored the workshop for scientists who study terrestrial, aquatic, and TAI systems to assess the state of the science in coupled terrestrial and aquatic ecosystems and to develop a strategy for advancing Earth system research at the TAI (see Appendix 3: Workshop Breakout Questions, p. 67; Appendix 4: Workshop Participants, p. 69). The workshop's goal was to identify critical scientific knowledge gaps that limit the ability to represent TAIs in predictive models, supporting the DOE BER mission to understand complex biological and environmental systems. This interface is of particular concern to BER's Climate and Environmental Sciences Division, which leads DOE efforts to enhance

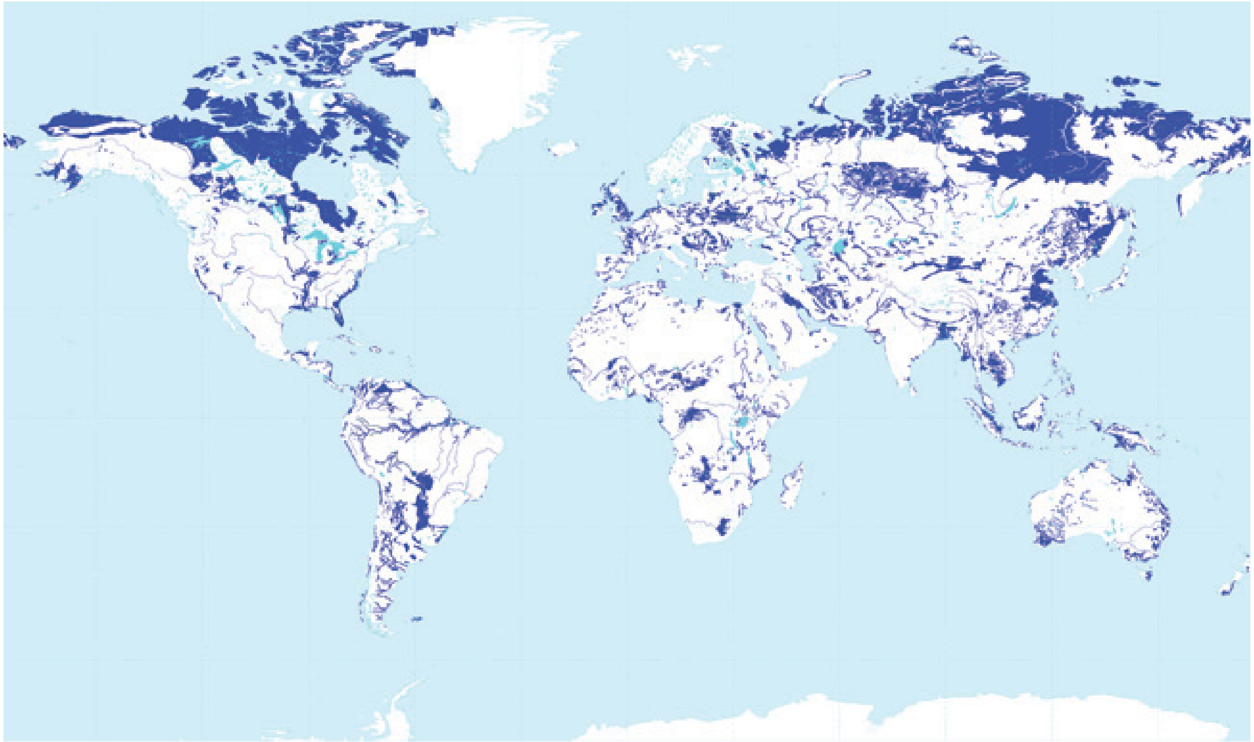
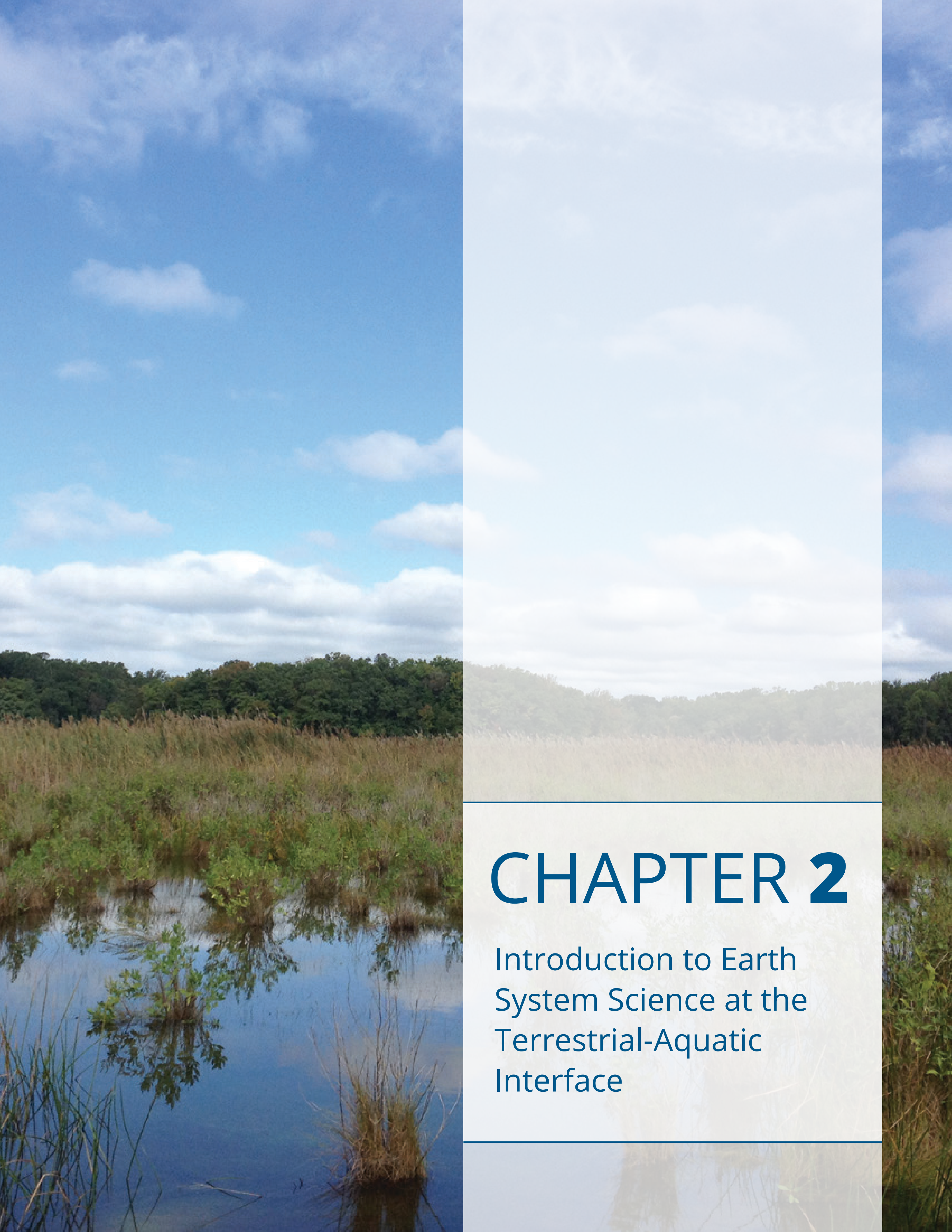


Fig. 1. Areas Dominated by Terrestrial-Aquatic Interfaces (TAIs). TAI ecosystems (dark blue) are ubiquitous across the globe. [Image courtesy U.S. Department of Agriculture Natural Resources Conservation Service]

predictive capabilities of the Earth system as a whole. The assembled community discussed (1) the state of knowledge with respect to understanding key TAI processes; (2) interdependencies among terrestrial, TAI, and aquatic systems; (3) research tools such as databases, technologies, observational approaches, and models; and (4) key research priorities necessary to improve predictive understanding of this critical ecosystem interface.

The workshop affirmed the view that TAI systems are critical interfaces defined by physical, chemical, and biological interactions that produce rapid rates ("hot spots") of biogeochemical processes. These interfaces are not merely conduits for the exchange of soluble and particulate materials among plants, soils, water bodies, and the atmosphere, but rather biogeochemically and hydrologically dynamic bodies where materials are transformed as they flow through and interact with TAI systems. While TAIs often are classified as wetlands, marshes, mangroves, swamps, peatlands, floodplains, riparian zones, hyporheic zones, lake margins, groundwater seeps, or similar transitional areas, the workshop highlighted the fact that such designations fail to articulate the unique traits that make TAIs important features of the Earth system. Terrestrial-aquatic interfaces support unique biological communities, rapid rates of biological productivity and microbial activity, high temporal and spatial variation in oxygen supply, carbon-rich soils, high potential greenhouse gas emissions, and sensitivity to anthropogenic disturbances and climate change impacts. Although TAIs are limited in global areal extent, at the landscape scale they collectively form a spatially extensive network that regulates global biogeochemical cycles (see Fig. 1, this page).



CHAPTER 2

Introduction to Earth System Science at the Terrestrial-Aquatic Interface

2

Introduction to Earth System Science at the Terrestrial-Aquatic Interface

Terrestrial-Aquatic Interfaces as a Concept

Conceptually, the "interface" of terrestrial and aquatic systems calls to mind a sharp boundary such as a river bank, a lake shore, the edge of a salt marsh, or even the top of the water table. However, a helpful approach is to view terrestrial-aquatic interfaces (TAIs) from the perspective of the processes that control the fluxes and transformation of mass and energy in ecosystems that bound such physical interfaces. From this perspective, TAIs take on complex, spatially and temporally dynamic scales. These scales are best defined by gradients in specific processes that are relevant to understanding and quantifying fluxes and transformations in Earth and environmental systems.

The multiscale nature of temporal and spatial process gradients across TAIs represents one of the great research challenges in Earth science and is a major reason that TAI systems remain poorly understood. For example, in regions with very high rates of physical change and biogeochemical transformation, the relevant scales for both observations and prediction may be on the order of nanometers and seconds. Conversely, system-scale hydrological drivers such as precipitation and sea level rise dictate measurements and predictions at watershed to global scales over years to decades. Coupling such divergent process representations is a fundamental challenge in advancing understanding and modeling of Earth systems.

The scientific and stakeholder objectives of the observer determine how TAIs are viewed and defined. For a scientist or stakeholder focused on the coupling of wetland systems to terrestrial systems, the wetland-aquatic boundary may demarcate areas of primary interest (land-wetland coupling) from areas of less interest (wetland-aquatic coupling). From this perspective, the TAI would extend from the wetland into the terrestrial system over large distances but diminish rapidly from the wetland into the aquatic realm. Conversely, for a researcher focused on estuaries, large rivers, and open water, the TAI may extend from the wetland into the aquatic system over large distances and less so into the terrestrial realm. Development is needed of observational and modeling approaches that span all viewpoints while remaining faithful to the process representations, both within the interface regions and in the more traditional aquatic and terrestrial systems. This scientific challenge requires integrated research across physical, chemical, and biological scientific disciplines and novel modeling strategies both in spatial and process representations and in computational architectures. Interactions inherent in TAIs arise from fundamental Earth and environmental system processes. Hydrology is the most important determinant of TAI structure, function, and variability in time and space. Indeed, TAIs are an inevitable outcome of water cycling within terrestrial and aquatic systems. Water chemistry undergoes dramatic change as precipitation passes through plant canopies, soils, aquifers, streams, rivers, lakes, and estuaries. In the process, the flow and accumulation of water drive changes in geomorphology, soils, biogeochemistry, and ecology across terrestrial, wetland, and aquatic ecosystems. Such changes are especially important where terrestrial and aquatic ecosystems meet across a TAI, including during extreme events such as flooding or low flows.

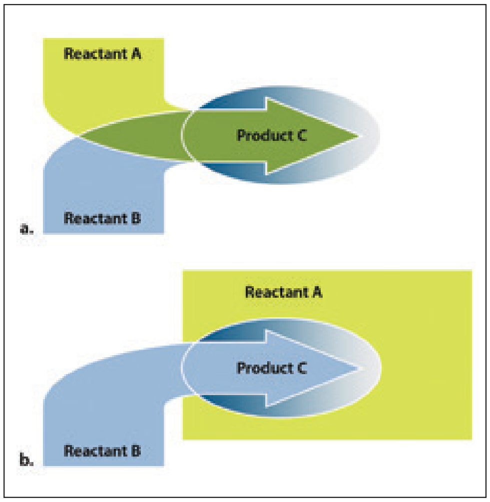


Fig. 2. Hot Spot Formation. Terrestrial-aquatic interfaces support high rates of biogeochemical processes because hydrologic flow (arrows) causes two or more reactants to intersect. Two common scenarios are shown. [Modified and reprinted with permission from Springer from McClain, M. E., et al. 2003. "Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems," *Ecosystems* **6**(4), 301–12. © 2003 Springer-Verlag New York, Inc.]

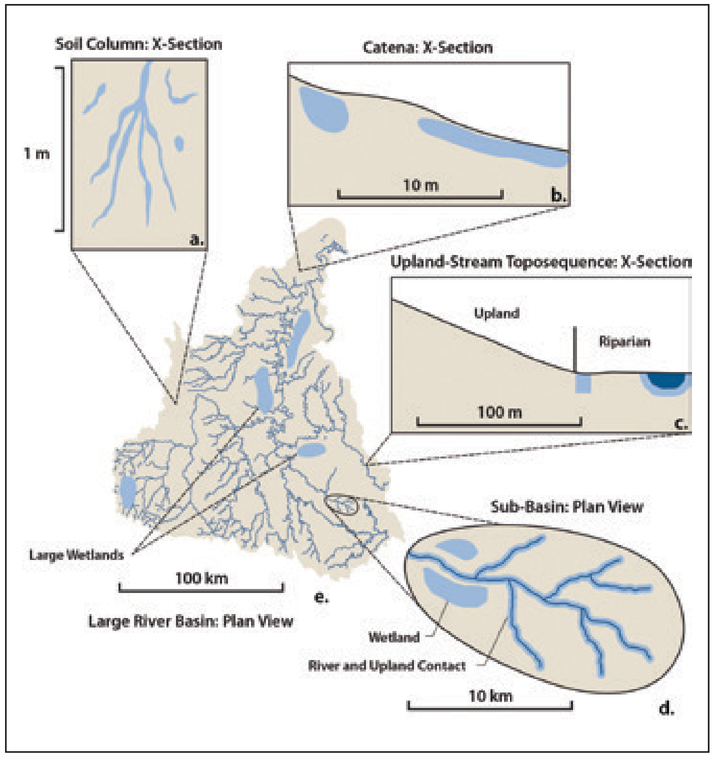


Fig. 3. Hot Spots at Multiple Spatial Scales. Terrestrial-aquatic interfaces (TAIs) are classic examples of hot spots, a concept based on differences in process rates in space and independent of scale. TAIs occur at the scale of **(a)** soil microsites, **(b, c)** hill slopes, **(d)** small watersheds, and **(e)** large watersheds. [Modified and reprinted with permission from Springer from McClain, M. E., et al. 2003. "Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems," *Ecosystems* **6**(4), 301–12. © 2003 Springer-Verlag New York, Inc.]

Fundamental Concepts Relevant to Terrestrial-Aquatic Interfaces

Terrestrial-aquatic interfaces are not passive boundaries across which water, carbon, other solutes, and particles move but dynamic transition zones where hydrology, biology, and geochemistry converge to create high process rates of outsized importance to element cycling (see Fig. 2, this page). TAIs typically are small in areal extent compared with that of the landscape matrix in which they are embedded, but they are highly important to biological and geochemical element cycling. Such regions have been referred to as hot spots. The same concept applies to time, associating the term "hot moments" to punctuated periods of intense transport and processing (McClain et al. 2003). These concepts are central to understanding the potential rewards and the challenges of a research initiative focused on TAIs.

Hot spots occur at scales ranging from soil aggregate microsites to large wetlands embedded in landscapes (see Fig. 3, this page). Examples of the range of spatial scales embodied by the hot spot concept include (1) anoxic microsites within soil aggregates or pedons (Sexstone et al. 1985; Keiluweit et al. 2016); (2) oxic microsites around wetland plant roots (Armstrong and Armstrong 2001); (3) hyporheic flow paths (Hedin et al. 1998; Harms and Grimm 2008); (4) discrete vegetation patches (Troxler et al. 2014); and (5) intertidal or semiflooded wetland landscapes (Bridgham et al. 2006). The hot spot concept as applied to TAIs often refers to biological processing of elements under conditions of varying oxygen availability or, more accurately, varying reduction-oxidation (redox) potential. Fluctuations between aerobic and anaerobic conditions drive transformation and cycling of redox-sensitive elements such as carbon, nitrogen, organic matter, iron, manganese, and sulfur. Redox processes in TAI systems ultimately regulate climate and environmentally relevant phenomena such as greenhouse gas emissions and preservation of organic carbon in soils. The hot spot–hot moment concept explains a large body of research that shows TAI processes are quantitatively important at basin, landscape, and global scales (see sidebar, Hot Spots and Hot Moments, this page). Riparian forests remove as much as 50% of nitrogen loading to streams where hydrologic flow intersects the root zone (Vidon et al. 2010). Coastal wetlands account for 0.2% of ocean area but 47% of organic carbon burial (Nelleman et al. 2009). Small water bodies disseminated across the landscape account for 50% of sediment accumulation and organic matter processing in terrestrial landscapes (Smith et al. 2002). Natural wetlands represent less than 10% of the land surface while constituting the largest single source of atmospheric methane (CH_4) and ~30% of mean global emissions (Paudel et al. 2016). Patterns of atmospheric circulation near coasts concentrate dry nitrogen deposition over land, creating large-scale hot spots of nitrate (NO_3) and ammonium particulate deposition that are two to five times higher over land than water (Loughner et al. 2016). The fields of Earth system science and ecohydrology have only recently begun to document the importance of hot spots and hot moments across scales from soil aggregates to hillslopes to watersheds.

Hot Spots and Hot Moments

Terrestrial-aquatic interfaces (TAIs) exhibit very high spatial and temporal variation in biogeochemical processes. Process rates in TAIs may differ by orders of magnitude from those in adjacent areas, making these interfaces areas of "outsized" weight in biogeochemical budgets. Ecologists have adopted the terms hot spots and hot moments to describe the phenomena in which small areas or short time periods account disproportionately for changes in a process of interest. TAIs are classic examples of hot spots and hot moments. The same concept exists in other disciplines; hydrology recognizes hot spots in the form of preferential flow paths and hot moments in the form of peak flows. The terms connote the relative magnitude of a process, not necessarily the frequency. A hot spot can be continuous over time and hot moments can occur regularly. The terms are not typically used as synonyms of extreme events, which tend to be less predictable.

Moreover, only recently have predictive models incorporated hot spots that describe nutrient dynamics in TAI systems (Arora et al. 2015).

Terrestrial-aquatic interface systems must be understood as more than boundaries or transition zones, rather as unique ecosystems in and of themselves. Characterized by a tight interdependence of hydrology, soils, plants, and microbes, TAIs produce unique biological communities compared to their terrestrial and aquatic counterparts.

The location of TAIs at boundaries between land, ocean, and rivers makes them highly susceptible to extreme hydrological and weather events such as hurricanes and floods. Although such events constitute hot spots and hot moments in the strictest sense, they tend to be far less predictable and are better described as "extreme events." These events cause sudden, dramatic, and transitory changes in environmental conditions

that have long-term consequences for ecosystems. For example, Hurricane Andrew caused intense mortality of mangrove forests in the southwest coastal region of Florida (Doyle et al. 1995). By contrast, sediment deposition from Hurricane Wilma increased mangrove soil fertility and soil elevation, both of which may have long-term benefits for mangrove forest productivity (Castañeda-Moya et al. 2010). Thus, extreme events can cause positive or negative feedbacks on TAI ecosystem structure and function, depending on the event's intensity and frequency (Conner et al. 2014). The impact of extreme events is more likely to be negative (e.g., sea level rise) in systems already compromised by human activities such as water diversions, but the feedbacks between such events and ecosystem structure and function are poorly understood.

Human activity is an important source of disturbance in TAI systems (Pelletier et al. 2015). These interfaces are highly sensitive to changes in climate, environment, and land use, because TAIs are strongly influenced by local and nonlocal drivers. Coastal regions and river corridors are often areas with the greatest population densities and land-use intensities. Both of these factors increase the likelihood of sudden changes in ecosystem structure and function resulting from disturbance and limit a system's capacity to adjust to change. Coastal wetlands show a high capacity to adapt to sea level rise (Kirwan and Megonigal 2013) and high susceptibility to "marsh drowning" (Voss et al. 2013). In time, extreme events may become more common in many regions (Katz and Brown 1992; Milly et al. 2008), and human activities may continue to alter TAIs. Thus, the scientific community must seek to understand and develop new tools to analyze a future for which there are no historical analogues that include exposure of TAIs to chronic instability and fluxes.

Historical Perspectives on Terrestrial-Aquatic Interfaces

Scientists working in a wide variety of disciplines have developed a rich reservoir of concepts, data, and models that relate in some fashion to TAI systems but have never integrated these elements to advance a holistic understanding of Earth system science. Several proposed conceptual frameworks explain changes in the relative importance of TAI processes across spatial scales from headwater basins to coastal zones. These concepts include a river continuum (Vannote et al. 1980), nutrient spiraling (Newbold et al. 1981), hyporheic corridors (Stanford and Ward 1993; Harvey and Gooseff 2015), flood pulse (Junk et al. 1989), outwelling (Odum 1980), and the wetland donor-receptor-conveyor (Brinson 1993). Scientists can use elements of such conceptual frameworks to develop a holistic understanding and modeling framework for TAI processes. For example, under the river continuum concept (see Fig. 4, p. 10), governing the flux of materials that move from terrestrial systems to surface waters are streambed physical dimensions and the characteristics of near-shore vegetation, such as stem density that affects hydrology. In this case, narrow (generally low-order) streams maximize fluxes of terrestrial material into surface water, while wide (generally higher-order) streams and rivers maximize the potential for uptake of terrestrial material, such as terrestrially derived inorganic nutrients, by in-stream primary producers. All these conceptual frameworks highlight important interactions and connections whereby (1) geomorphic features provide the physical template across and through which water moves; (2) water flow and spatial distribution strongly influence the availability of resources to biological agents; and (3) biological agents transform resources in ways that influence their fate [e.g., mineralization of dissolved organic matter to carbon dioxide (CO_2)]. Despite this rich conceptual framework, only recently has the scientific community fully appreciated the quantitative importance of TAI processes to the Earth system.

With the community's evolving view of the role of these systems in regional and global budgets, many groups are integrating representations of TAI processes into Earth system models (ESMs) to a limited extent (e.g., wetland processes; for a review, see Xu et al. 2016a). The history of efforts to model the

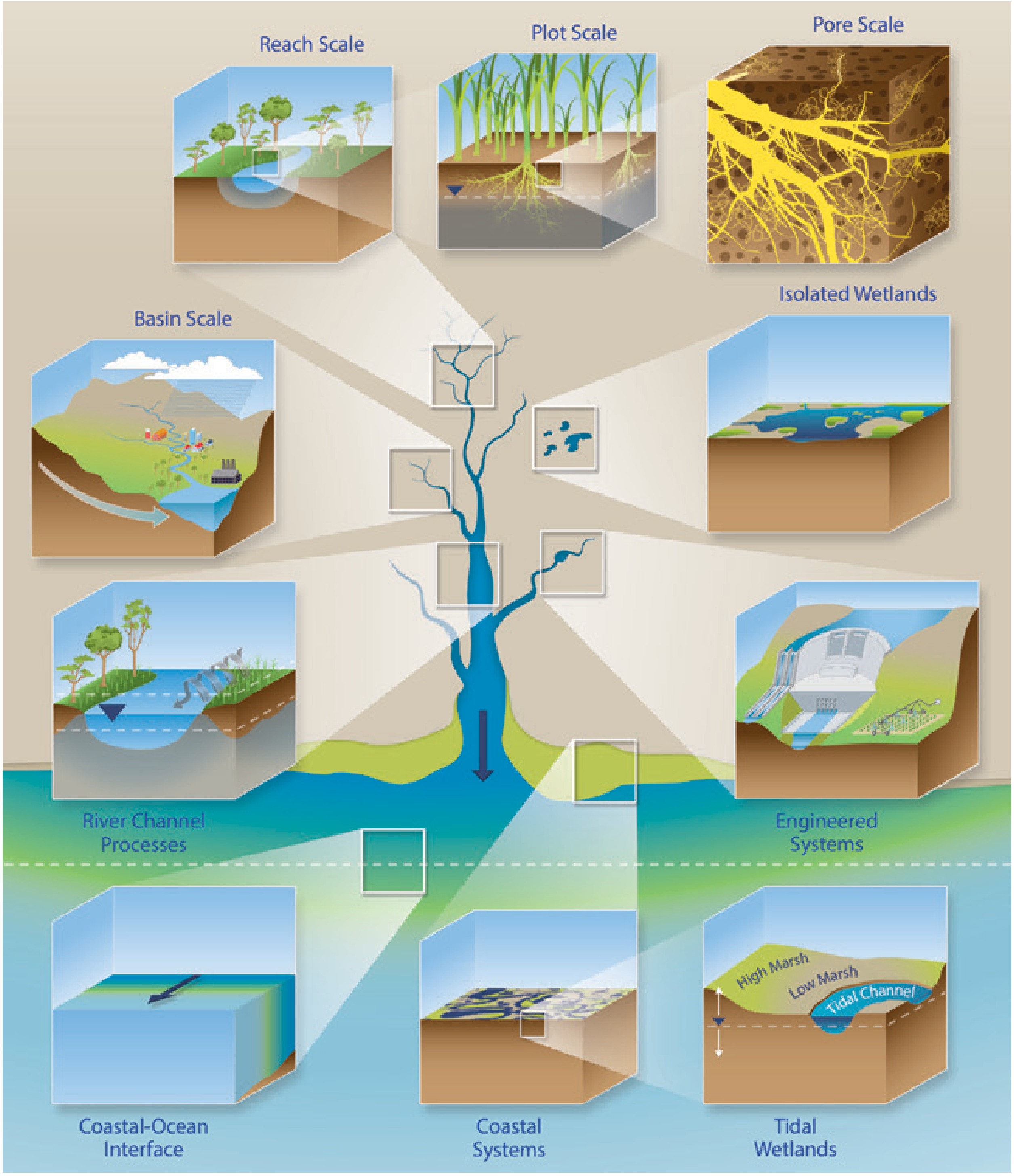


Fig. 4. Terrestrial-Aquatic Interfaces (TAI) Continuum. This illustration shows the differences in spatial scale of some of the commonly studied systems that TAI research seeks to integrate, namely interfaces associated with headwater streams, rivers, wetlands and floodplains, estuaries, and coasts. These subsystems are connected to one another through hydrology, geomorphology, solute and particulate transport, and ecological relationships, forming an integrated terrestrial-aquatic continuum from land to ocean.

global carbon cycle illustrates how TAI concepts have changed. Early box models of the Earth's carbon cycle included lateral carbon transfer from land to the ocean (Sarmiento and Gruber 2002; Schlesinger and Bernhardt 2013). However, there was no processing of terrestrial carbon either at TAIs or in the water bodies through which carbon moved before reaching the ocean. Now clearly evident is that the transformation of terrestrial materials in TAI systems is quantitatively important in Earth and environmental systems. Although modest advances have been made in modeling these processes, they are isolated within TAI or riverine systems. Indeed, there have been minimal efforts to couple terrestrial-TAI-aquatic processes. As the following discussion indicates, where progress has been made, the TAI system still is often treated as a boundary condition of the terrestrial or aquatic system rather than as a separate system. The goal of such models was to understand carbon and nutrient flux and processing in fully aquatic systems, with no attention paid to transformations occurring in TAIs.

The original conceptualization of aquatic systems was that of a passive pipe because transformations were not known to occur during transport through the aquatic continuum (Cole et al. 2007; see Fig. 5a, this page). Continuing with the carbon cycle example, this concept began to change with reports of substantial CO_2 degassing from aquatic systems (Richey et al. 2002; Frankignoulle et al. 1998) and significant carbon burial during transport (Tranvik et al. 2009; Sabine et al. 2004). These studies led to a reconceptualization of aquatic systems as active pipes where transformations of terrestrial carbon occur (Cole et al. 2007; see Fig. 5b, this page). A recent elaboration in the form of the Pulse-Shunt Concept recognizes that large "pulse" releases from terrestrial systems "shunt" materials downstream, bypassing areas where processing normally would occur and effectively changing the active pipe into a passive pipe (Raymond et al. 2016). TAI systems such as wetlands are captured by these active-pipe concepts but also are considered to be either terrestrial or fully aquatic systems. The TAI concept takes these conceptual models a step further by acknowledging that TAI systems lie between those that are fully aquatic or terrestrial, have unique carbon cycles, and exercise important control over net fluxes of CO_2 and

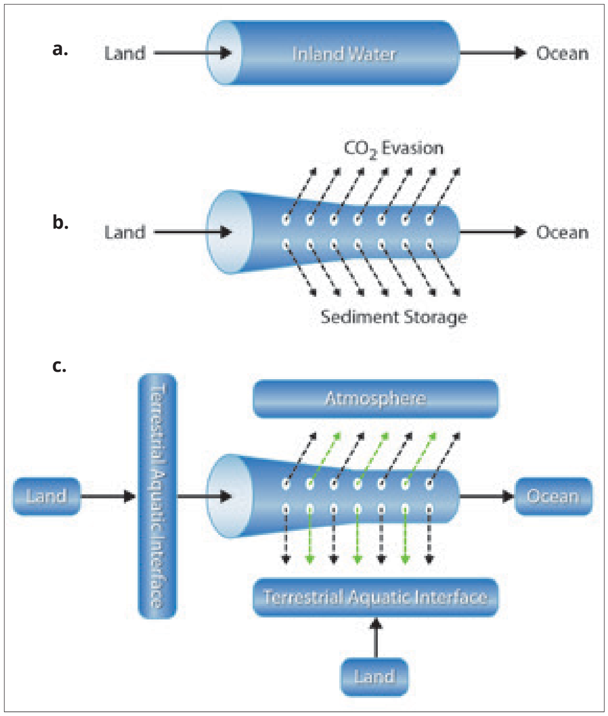


Fig. 5. Conceptual Models of the Coupling Between Terrestrial and Ocean Carbon Cycles. **(a)** Aquatic systems transport terrestrial carbon to oceans with little or no processing. **(b)** Aquatic systems actively remove terrestrial carbon during transport through deposition of particulate carbon in sediments and microbial mineralization of organic carbon to carbon dioxide. Terrestrial-aquatic interfaces (TAIs) such as wetlands generally are considered to be part of the terrestrial system. **(c)** Represented as distinct systems, TAIs share both terrestrial and aquatic characteristics. TAIs can act as both net sinks (black arrows) and sources (green arrows) of carbon to aquatic systems and the atmosphere under different conditions. [Modified and reprinted with permission from Springer from Cole, J. J., et al. 2007. "Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget," *Ecosystems* **10**, 172–85. © 2007 Springer Science+Business Media, LLC]

particulate carbon (see Fig. 5c, p. 11). For example, wetlands are TAI systems where terrestrially derived carbon is deposited, buried, and preserved and where CO_2 evasion takes place; thus, wetland processes dramatically control the size and nature of carbon fluxes. Plant production within TAIs is the largest source of organic matter preserved in TAI soils. Changes in plant growth resulting from elevated CO_2, flooding, or other factors not only alter carbon inputs, but can change a "stable" carbon pool into an "unstable" pool by increasing the availability of organic carbon and oxygen (Mueller et al. 2016; Wolf et al. 2007). Likewise, TAI systems such as tidal marshes are sources of dissolved organic carbon for aquatic systems and regulate processes such as photochemical and microbial carbon processing during transport from a TAI to receiving waters (Vähätalo and Wetzel 2004; Tzortziou et al. 2007, 2011).

Despite the progress made in including aquatic ecosystems in carbon budgets, the role and contributions of TAIs and fully aquatic ecosystems in storing and transporting carbon are not clear, and this knowledge is necessary for a proper determination of their importance. A recent analysis of carbon exported from terrestrial soils to aquatic systems suggests that storage along the continuum of freshwater bodies, estuaries, and coastal rivers may be much greater, by 0.5 petagrams of carbon per year, than previously thought (Regnier et al. 2013). This finding has important implications for understanding of the global carbon budget. For example, budgets of carbon flux through terrestrial-TAI-aquatic systems have been used to (1) constrain hydrologic controls on atmospheric CO_2 levels through time (Berner 1994; Maher and Chamberlain 2014), (2) estimate the net flux of CO_2 between the ocean and atmosphere (Jacobson et al. 2007), and (3) balance the production and oxidation of organic matter on land (Sarmiento and Gruber 2002).

Understanding of nutrient fluxes also has evolved considerably. Many studies in recent decades have elucidated key controls on terrestrial nutrient transfers to the aquatic continuum. In general, research has documented a strong anthropogenic influence on nutrient fluxes from agriculture and urban land management (Jordan and Weller 1996; Coutler et al. 2004; Broussard and Turner 2009). TAI and aquatic processes are clearly important in the uptake, transformation, and burial of nutrients in landscapes, and large amounts of anthropogenic nutrients may be stored and mobilized in future years despite the successful management of nutrient loading (Powers et al. 2016). Furthermore, models indicate that rapid climate and other environmental changes could mobilize a greater percentage of important nutrients to TAIs, streams, and rivers due to a decrease in residence time in the terrestrial systems from where they originate (Howarth et al. 2012).

Models of Coupled Terrestrial, TAI, and Aquatic Processes

Historically, the needs specific to terrestrial, certain wetland ecotypes, or aquatic ecosystems have driven models of TAI processes and systems. Further, very few of these models attempted to couple the full suite of processes that occur across terrestrial-TAI-aquatic systems (see Fig. 6, p. 13). In ESMs, processes taking place in TAIs such as nontidal mineral soil wetlands, coastal wetlands, and peatlands are simulated using modules designed for upland ecosystems. ESMs do not have mechanistic modules to describe the biogeochemical transformations that occur as materials flow across TAIs from upland to aquatic systems. Although the ability to model biogeochemical transfers at regional to global scales has evolved (e.g., for the leaching of NO_3 fluxes; Zhu and Riley 2015), there is a need for significant improvement. Many models use nutrient fluxes measured or estimated at the scale of large basins to continents, capturing the aggregated effects of transport and processing but missing critical hot spots at the TAI scale. Furthermore, most key processes in these models are represented at long temporal scales despite a growing body of literature stressing the importance of short-term, transient hydrologic events in controlling nutrient

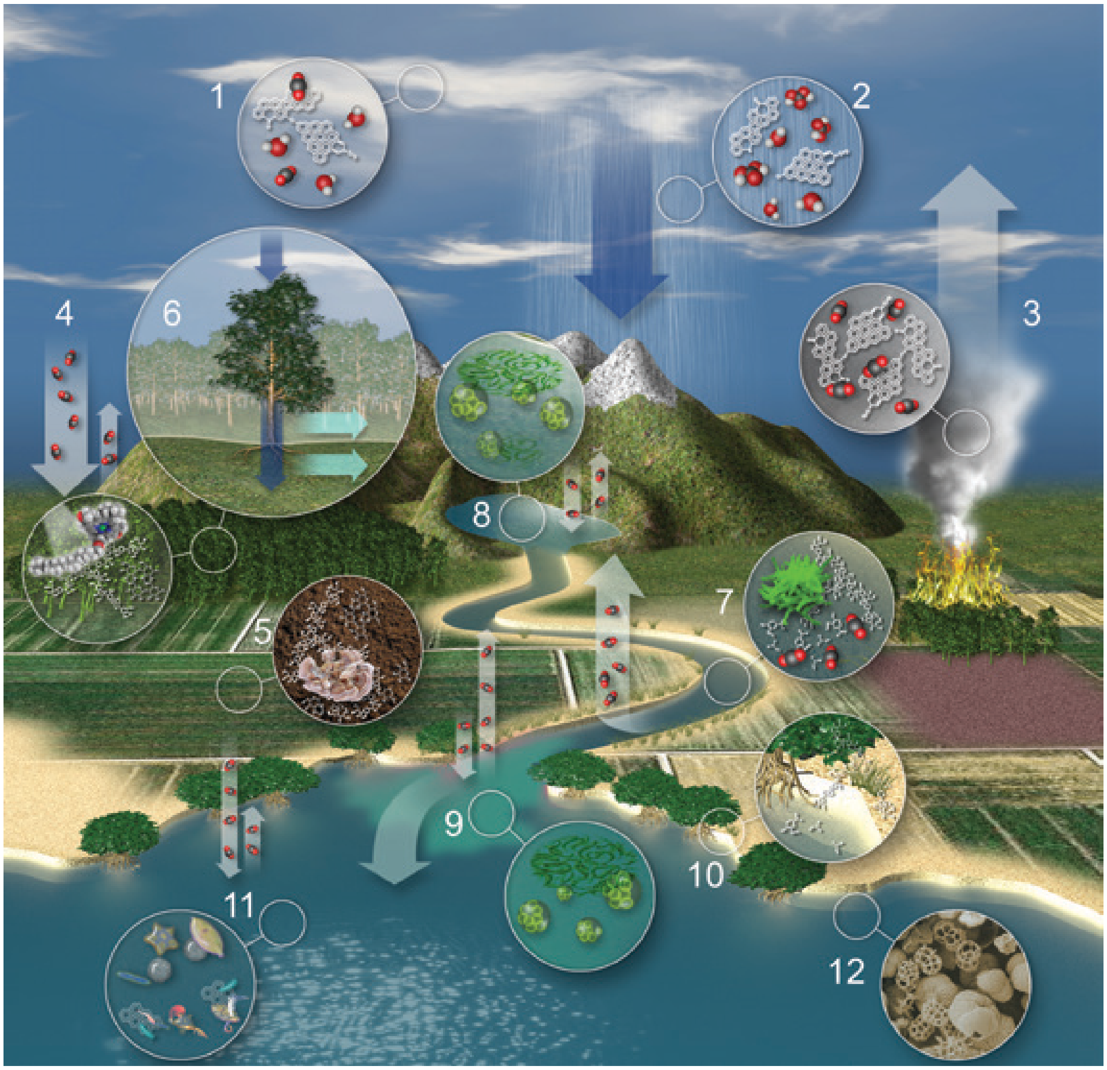


Fig. 6. Carbon Movement Through Terrestrial-Aquatic Interfaces (TAIs). Water is a key agent, moving biogeochemical constituents through the atmosphere and the TAI continuum. **(1)** Atmospheric particles promote cloud formation. **(2)** Raindrops absorb carbon, carrying it to Earth. **(3)** Other carbon sources in the atmosphere include burning and gas fluxes [e.g., carbon dioxide (CO_2)]. **(4)** Plants fix CO_2 through photosynthesis, converting it into more complex forms of biomass. **(5)** Plant litters and exudates enrich the soil with organic carbon. **(6)** Water transports carbon through forest canopies (throughfall and stemflow), and biogeochemical transformations occur in soils and sediments and during overland flow. **(7)** Organic carbon is decomposed microbially and abiotically, returning CO_2 to the atmosphere and producing biomass and metabolites. **(8)** Carbon is stored and transformed in open water bodies. **(9)** River plumes may be enriched in nutrients. **(10)** Coastal marshes can both store and export carbon. **(11)** Continental shelves and oceans can absorb atmospheric CO_2, biologically storing carbon in **(12)** marine sediments. [Reprinted under a Creative Commons Attribution License (CC BY) from Ward, N. D., et al. 2017. "Where Carbon Goes When Water Flows: Carbon Cycling Across the Aquatic Continuum," *Frontiers in Marine Science* **4**, 7. © 2017 Ward, Bianchi, Medeiros, Seidel, Richey, Keil, and Sawakuchi]

export trajectories and magnitudes (Hall et al. 2013; Raymond et al. 2016).

The vegetation models for TAI systems are in their infancy. For instance, the transport of gases (e.g., oxygen and CH_4) through wetland plants is a critical feature of some TAIs that is needed to model carbon and greenhouse gas dynamics. The wetland biogeochemistry modules in both the Community Earth System Model and the Accelerated Climate Modeling for Energy project represent these processes by using upland plant production and respiration to drive the production of CH_4 and transport it and other gases through hypothetical wetland plant tissues (Riley et al. 2011). Similarly, vegetation models in ESMs do not have explicit representations of how salinity affects vegetation growth and mortality in coastal zones and, therefore, cannot mechanistically explore carbon-nutrient feedback in tidal wetland ecosystems. Finally, most models have only static vegetation distributions, which lack the ability to dynamically respond to changes in important drivers such as flooding frequency and salinity or use simple formulations that ignore key physiological processes such as photosynthetic rates, flooding stress, salinity stress, and intraspecific competition (Ge et al. 2016). Such models almost certainly will fail to correctly simulate realistic vegetation responses and associated interdependencies or feedbacks under future novel climate conditions.

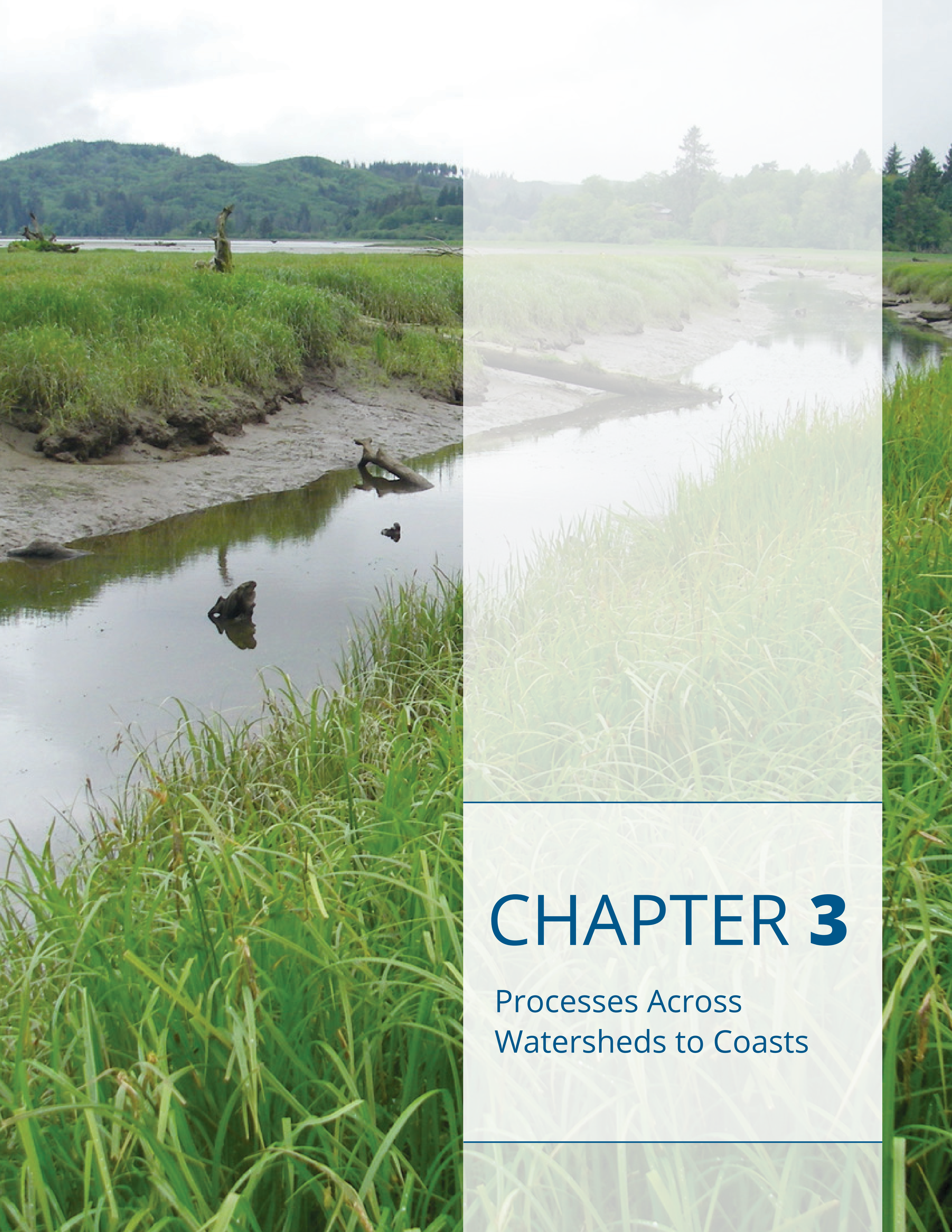
Terrestrial-Aquatic Interfaces as a Transdisciplinary Challenge

The involvement of numerous scientific disciplines, each of which contributes to the study of wetlands, rivers, and coasts, is evident from the background described in this section. In general, they include the classic marriage of the environmental and life sciences that established the foundation of ecology (Moore 1920). Some of the more important environmental science fields that address TAI systems include hydrology, meteorology, oceanography, geology, and geomorphology. Among the important life sciences are ecology, microbiology, and plant physiology. Hybrid disciplines that encompass biotic and abiotic components also are highly relevant, such as limnology, biogeoscience, ecohydrology, ecogeomorphology, soil science, and ecology.

The increasingly large number of disciplines required by research teams to address complex problems is now the rule, not the exception (Börner et al. 2010; Ledford 2015). Arguably, the inherent need to bring multiple disciplines to address research problems in terrestrial-aquatic ecosystem science is the very reason that such large research gaps remain—historically, interdisciplinary studies have received low levels of funding (Bromham et al. 2016). There are rich scientific literatures to be mined in the ecology of wetlands, riparian zones, forests, coastal systems, estuaries, landscapes, soils, and other nonecological-centric disciplines such as hydrology and climate change science. The breadth and diversity of these disciplines pose distinct challenges for TAI research if disciplinary activities remain independent and fragmented. For instance, different disciplines use different vocabulary words to describe the same phenomena and different theoretical frameworks to underpin research and modeling approaches; furthermore, researchers attend disciplinary-centric conferences. Clearly, lessons learned while working through interdisciplinary challenges will be useful to a successful research program in terrestrial-aquatic ecosystems (e.g., National Research Council 2005; Brown et al. 2015).

Transdisciplinary science has the potential to reveal fundamentally new solutions, whether from knowledge or models, requiring input from more than one discipline. This contrasts with *multidisciplinary* science where scientists collaborate but the disciplines remain isolated, and *interdisciplinary* science where some results are shared and integrated but others are not. Human systems clearly need to be considered in any study of TAI systems because of the immensity of their effects on key physical processes (Liu et al. 2015). Transdisciplinary science also incorporates multiple stakeholders (Klenk et al. 2015), which for terrestrial-aquatic ecosystems could include mission agencies in

addition to the U.S. Department of Energy, such as the National Oceanic and Atmospheric Administration, U.S. Geological Survey, and National Aeronautics and Space Administration. This report develops the technical basis and need for synthetic TAI research. Nevertheless, an important early phase in any TAI research program is to canvass the sciences and stakeholders mentioned herein to synthesize and evaluate promising areas of research beyond the scope of this workshop report.



CHAPTER **3**

Processes Across Watersheds to Coasts

3

Processes Across Watersheds to Coasts

A major challenge to incorporating the terrestrial-aquatic interface (TAI) into Earth system models (ESMs) is the familiar issue of capturing and integrating fundamental physical, chemical, and biological processes as they change across scales of space and time. This chapter describes key TAI features to capture in Earth system science and models and considers how they vary over spatial and temporal scales. Illustrated herein are the differences in spatial scale of some of the commonly studied systems that TAI research seeks to integrate, namely interfaces associated with headwater streams, rivers, wetlands and floodplains, estuaries, and coasts (see Fig. 4, p. 10). These subsystems are connected to one another through hydrology, geomorphology, solute and particulate transport, and ecological relationships, forming an integrated terrestrial-aquatic continuum from land to ocean. These concepts are understood to apply in principle to TAIs other than those illustrated in this chapter.

Fundamental Processes

Important biogeochemical phenomena reach peak expression at the boundaries where distinct Earth systems intersect. TAI systems tend to exist in a state of disequilibrium driven by the influx, production, transformation, and export of chemicals, sediments, organisms, and energy. The challenge of scaling across space and time requires understanding that certain fundamental processes operate across all scales but that the scale changes the extent to which a given process dominates biogeochemical cycling. Fundamental processes occur everywhere but often are heterogeneously distributed and expressed differently across scales.

Transport Domains

Solute transport is perhaps the most fundamental TAI process that must be captured within ESMs. Solutes can be transported by advection and diffusion. Whether advection or diffusion dominates depends on the rate of water movement relative to rates of solute concentration change resulting from chemical and biological processes. For fast-moving waters characteristic of many low-order streams, particularly in mountainous areas, advection dominates solute transport. For slow-moving water bodies, such as groundwater and surface water within certain wetlands, advection diminishes and diffusion exerts dominant control of solute transport. For all but coarse sands and gravels under fast-flowing waters, soils and sediments greatly enhance the diffusive component of solute transport. In places where advection- and diffusion-controlled domains intersect, steep chemical gradients arise as a result of solute delivery from the advection-dominated source (i.e., flowing water) and the transformation of solutes into different chemical forms through biological or chemical processes in the diffusion-dominated zone. For example, advection rapidly delivers nitrate (NO_3) in stream water as a solute; NO_3 then diffuses into stream-bottom soils where it resides long enough to be used by microorganisms for cell building (anabolism) or converted to nitrogen gas through denitrification. In the latter case, nitrogen then diffuses from the site of production into the advecting waters. An example of a rapid transition from advection- to diffusion-dominated processes that applies to water columns (i.e., does not require soils or sediments) is the stratification of water resulting from differences

in temperature or salinity, leading to boundary layers where diffusion controls solute flux between layers.

Media Structure and Pore Sizes

Soils and sediments have similar inherent diffusional boundaries caused by constrained water flow through porous media (see Fig. 7, this page). Particulate matter of soils and sediments is made up of different-sized grains, ranging from clays to sands. Between the grains lies a porous network of voids through which solutes can travel when filled with water, or gases when filled with air. For clays and silts, attractive forces resulting from particle charges and bridging ions, along with organic and inorganic cements, lead to an aggregated structure. This framework results in a composite of pore sizes, with the smallest pores being inside aggregates and the largest pores between aggregates. Understanding the variation in pore domains and the chemical environments they create at fine scales is critically important because these domains and environments are the reaction sites for the biotic and abiotic processes that underpin the landscape-scale observations sought for prediction and modeling.

These pores are not perfectly connected, creating isolated pockets of solutes and solutions where chemical and biologically catalyzed transformations are almost entirely dominated by diffusion. In unstructured media, pore sizes vary proportionally to grain size, while structured media have a wide range of pore sizes. The distribution of pore sizes controls the relative influence of diffusion versus advection processes, whether they are considered at the scale of a soil aggregate, soil pedon, or landscape.

The pore network is an important characteristic of soils and sediments defined by the distribution and arrangement of pores of varying size, length, and continuity. In addition, a single pore may be quite heterogeneous in shape and size (e.g., diameter) along its length. As a result, soils may simultaneously provide continuous connectivity among pores and isolated pockets that present distinct chemical environments.

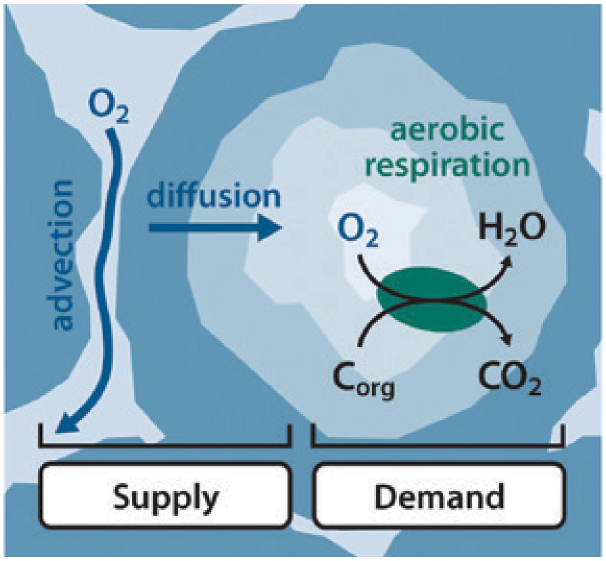


Fig. 7. Pore-Scale Processes. Illustrated is the balance between oxygen supply (via advection and diffusion) and demand (via microbial oxygen consumption) that is responsible for the formation of anaerobic microsites in well-structured upland soils. [Modified and reprinted with permission from Springer from Keiluweit, M., et al. 2016. "Are Oxygen Limitations Under Recognized Regulators of Organic Carbon Turnover in Upland Soils?" *Biogeochemistry* **127**(2–3), 157–71. © Springer International Publishing Switzerland 2016]

This arrangement explains the occurrence of anaerobic microsites in soil matrices that complicate efforts to model certain phenomena, such as the balance between methane (CH_4) and carbon dioxide (CO_2) production (measured at core, plot, or tower scale) in spatially scalable ways.

Porewater networks contribute to the dynamic hydrologic connectivity in TAI systems that exert control over organic carbon stability, but their control mechanisms are neither well understood, nor specifically addressed in mechanistic models at any scale. For example, different wetting processes (groundwater rise or rainfall) follow different physical flow paths that can change the solubilization and transport of spatially occluded carbon. Surface wetting from rainfall or melt

waters initiates a wetting front led by coarse, gravitationally filled pores (Todoruk et al. 2003); in contrast, when water rises upward from the groundwater, the wetting front is led by fine capillary pores (Yang et al. 2014). The result of these distinctions is that organic carbon in different pore-size domains is differentially vulnerable under different hydrologic scenarios.

Saturated Versus Unsaturated Conditions

Soils persistently inundated with water will conduct water through their largest pores, while diffusional forces will restrict transport through the smaller pores. Soils that are drained, permanently or intermittently, will retain water against gravity through a combination of forces—capillary and water adsorption (to solid particles)—that are collectively referred to as matric forces and will give rise to a matric potential. The ability of water to rise higher in smaller capillary tubes, as opposed to larger ones, is much like that of water rising higher through narrow pores than through wider ones. As a result, there are predictable patterns in how soil pores conduct water as soil transitions from being dry to wet and the reverse. At larger scales, the proportion of the landscape that is subject to saturated versus unsaturated flow affects hydrologic fluxes and the relative importance of advection versus diffusion processes in regulating biogeochemical transformations. The relative roles of saturated versus unsaturated sediment in coupled river, hyporheic, and groundwater settings provide a large potential for transient nutrient processing and the reversal of reduction-oxidation (redox) conditions. For example, in rivers that continually feed groundwater (i.e., losing rivers), the river and aquifer potentially can become disconnected, allowing an unsaturated zone to develop beneath the riverbed (Newcomer et al. 2016).

Microbial Communities and Processes

Microorganisms mediate biogeochemical cycles and directly drive the rapid pace and diversity of chemical transformations that define hot spots and TAIs. The well-established observation that most microorganisms have yet to be discovered is especially true in TAIs, where microbial species characteristic of both terrestrial and aquatic systems can dominate biogeochemical transformations. The high spatial and temporal variations in TAIs allow microorganisms adapted to a wide range of environmental conditions to co-exist, creating highly unique microbial assemblages supporting equally unique processes.

Terrestrial-aquatic interfaces are characterized by steep gradients in the availability of organic carbon substrates and terminal electron acceptors that support the metabolism of microbes and their abilities to respond to environmental factors such as pH and salinity. Resource and environmental gradients develop across TAI scales, from microbial habitats in soil pores to the rhizosphere to the landscape, and the gradients respond dynamically to changes in plant activity, hydrology, sediment deposition, and other factors. The complex multidimensional niche space created by these myriad intersecting gradients and the energetic constraints of anaerobic-aerobic cycles on their metabolic processes can select for microbial species with high niche specificity. For example, certain members of the archaea require a very narrow range of salt concentrations to actively cycle carbon (Arai et al. 2016), while other microorganisms require a narrow range of oxygen concentration or redox potential (Neubauer et al. 2002). The combination of steep gradients and high niche specificity among microorganisms produces unique microbial assemblages at all scales across which such gradients are expressed (Luna et al. 2013). The high niche specificity of TAI microorganisms and niche diversity may explain evidence that TAI microbial community composition is coupled less strongly to plant rhizosphere dynamics in TAIs than in upland terrestrial systems (Keller et al. 2013; Emerson et al. 2013; Prasse et al. 2015).

The redox potential exerts an overriding influence on the identity and activity of microorganisms in TAIs (see Fig. 8, p. 21) and on the structure of the intrinsic microbial communities (Reckhardt et al. 2015). Similarly, the activity of specific microorganisms with

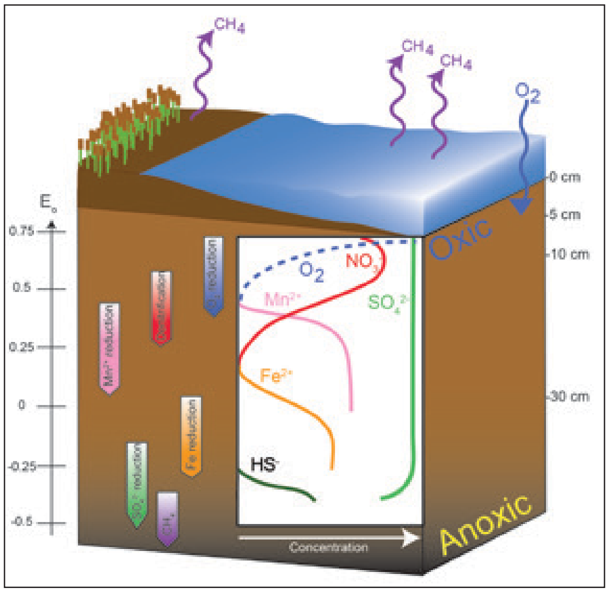


Fig. 8. Microbial Redox. Soil flooding in terrestrial-aquatic interface soils historically was thought to result in defined reduction-oxidation (redox) zonations that broadly span oxic conditions at the surface to anoxic conditions with depth. Some possible microbial electron accepting processes are shown as colored boxes in the soil at relative depth positions. In the white box, representative concentrations of key geochemical indicators of these redox processes also are shown. The corresponding position for each of these metabolisms is shown on the soil redox potential (E_o) tower scale on the left. More recent literature (Bethke et al. 2011; Keiluweit et al. 2016), however, suggests that these assumptions about soil redox zonations may be oversimplified, because they are impacted by soil chemical, biological, and physical properties that typically result in overlapping redox zones or zones distinguished on much finer resolved scales (aggregate or pore scale). [Image courtesy Lindsey Solden and Kelly Wrighton, Ohio State University]

specialized metabolic pathways is a dominant process that establishes redox gradients. Feedbacks between redox gradients and microbial activities drive the coupled biogeochemical processes that distinguish TAIs. As redox potential changes in space and time in response to factors such as hydrology or plant activity, microbial communities respond with changes in carbon cycling. For example, microbes favor degradation of cellulose and other plant polymers during aerobic phases but favor methanogenesis during anoxic phases (Arai et al. 2016).

The capacity of certain microorganisms to respire under anaerobic conditions is critical to the biogeochemical cycles of redox-sensitive elements such as iron, sulfur, and nitrogen, and indirectly to the cycling of elements that are not redox sensitive such as phosphorus (Algora et al. 2013; Arai et al. 2016; Reckhardt et al. 2015). Anaerobic metabolism is a ubiquitous process that occurs across terrestrial, TAI, and aquatic systems, but it reaches peak expression in TAIs because of tight coupling to aerobic metabolism (Megonigal et al. 2003). Anaerobic carbon metabolism requires oxidized forms of redox-sensitive elements, whereas many types of aerobic metabolism such as iron oxidation require reduced forms of these elements. Rapid cycling between oxidized and reduced-oxidation states leads to high rates of microbial metabolism in TAIs. Because oxygen is the dominant oxidant at the Earth's surface, oxygen availability strongly influences the spatial distribution of microbial processes. For example, microbial iron reduction generally is the more dominant process where TAIs meet terrestrial habitats (Luo et al. 2016). Factors that decrease the availability of oxidized iron, such as temperature or position along an oxygen gradient, lead to differences in the rates and forms of carbon emitted as gases or retained as soil organic matter (SOM; Bullock et al. 2013). Microbial iron metabolism is an indirect control on phosphorus cycling through sorption and co-precipitation processes, which vary in space and time depending on oxygen availability, salinity, tides, and other factors (Upreti et al. 2015). Cycles of deposition, remobilization, and transport lead to an iron conveyor belt in estuaries (Jordan et al. 2008). TAIs support a wide diversity of microbial nitrogen transformations including some (e.g., anaerobic ammonium oxidation or annamox) that are relatively recent discoveries (Burgin and Hamilton 2007). Oxygen availability regulates the pathways and rates of microbial nitrogen transformation and, ultimately, nitrogen persistence in

TAIs, ecosystem nitrogen availability, and water quality (Neubauer et al. 2013).

Environmental conditions regulate microbial activity in TAIs via a variety of mechanisms including the availability of substrates (e.g., terminal electron acceptors) and physiological limitations (e.g., pH tolerance). Salinity is an example of a factor that can act in both ways on TAI microbial metabolism—through ionic strength effects (Chambers et al. 2011) and through the availability of sulfate (SO_4^{2-}) as a terminal electron acceptor supporting SO_4^{2-}-reducing bacteria. The introduction of saline waters into tidal freshwater ecosystems simultaneously changes microbial community composition (Lv et al. 2016) and microbial activities such as rates of carbon mineralization (Weston et al. 2011). The impacts of salinity intrusion on soil carbon storage in TAI systems are mixed, with some reports suggesting higher net carbon storage (Hu et al. 2016; Hu et al. 2014) and others suggesting a decrease (Morrissey et al. 2014). Such discrepancies reflect a poor understanding of spatial and temporal variation; interactions among terrestrial, aquatic, and TAI biogeochemical processes; and factors that regulate microbial community composition. The impacts of salinity caused by sea level rise reporesent one example of the need for further research and experiment-model integration in TAI systems. Currently, there is no way to forecast how saline intrusion will operate through shifts in microbial species richness and diversity to change carbon, nitrogen, and phosphorus biogeochemical cycles (Kearns et al. 2016; Chambers et al. 2016; Weston et al. 2011). These changes include those in CH_4 emissions that will alter the radiative balance of coastal wetlands and estuaries (Poffenbarger et al. 2011; Weston et al. 2011).

Microbial communities also can affect physical processes in TAIs such as hydrologic flow. For example, in hyporheic zones microbial growth initiates a pore-scale negative feedback by physically occupying pore spaces as the microbes grow, eventually limiting the water infiltration that initially sustained their growth and decreasing rates of infiltration into aquifers (Newcomer et al. 2016). The effects of flow on microbes and microbes on flow are not unique to hyporheic zones but represent a process-level understanding of how large-scale, hydrologic flow and pore-scale, microbially driven biogeochemistry interact. Based on this understanding, it may be possible to integrate pore-scale processes and regional aquifer hydraulic gradients to predict whether river and hyporheic zones will behave as a sink or source of CO_2, especially, for example, where human modifications largely regulate climatic controls.

Plant Traits and Vegetation Dynamics

Plant processes are among the most fundamental forces that shape the dynamics of TAI systems. Ecological theory recognizes the central role played by plants (and other organisms) in ecosystem structure and function through concepts such as "ecosystem engineers" (Wright and Jones 2006), "foundation species" (Angelini et al. 2011), and "keystone species" (Paine 1995). Vegetation dynamics are particularly key in TAIs because of their strong influence on hydrologic and geomorphic processes (Hupp 1992; Camporeale et al. 2013; Gurnell 2014). The unique subset of all plant traits possessed by species growing in a given TAI system exerts direct control on the dominant operating processes. Thus, plant traits and vegetation dynamics are critical features needed in experiments and models to successfully couple terrestrial and aquatic systems.

Adaptation to flooding stress is a ubiquitous trait of vascular plant species found in TAI systems, with large consequences for carbon dynamics and biogeochemical cycles. Trees, shrubs, sedges, forbs, grasses, and all other types of emergent, floating, and submerged aquatic plants are aerobic organisms that require molecular oxygen to support respiration. Because oxygen diffuses 10,000 times more slowly in water than air, respiration demand for oxygen can quickly exceed supply, causing oxygen starvation of plant root respiration. TAI plant species have physiological adaptations for tolerating hypoxic conditions, but they also have

morphological adaptations that can increase oxygen supply to roots. These interface plants transmit oxygen from the atmosphere through specialized stem tissue (aerenchyma) to roots, a trait that supports root respiration but also supplies the critical electron acceptor oxygen to soil microbial communities. So-called "root oxygen loss" raises soil redox potential and supports important microbial processes such as aerobic SOM decomposition (Wolf et al. 2007), nitrification, iron oxidation, and CH_4 oxidation (Megonigal et al. 2003; Laanbroek 2010). As the primary source of organic carbon and oxygen in TAI soils, plants fundamentally regulate microbial communities and soil biogeochemical processes (Neubauer et al. 2005; Mueller et al. 2016).

Plants interact strongly with hydrology and geomorphology through complex feedbacks in TAIs. A dramatic example is in tidal wetland ecosystems where soil elevation is a dominating variable that integrates feedbacks among biology, hydrology, and geomorphology. Plants, which exist in a narrow range of flooding depth and duration governed by their adaptations to flooding, normally will exhibit a flooding optimum whereby either less flooding or more flooding reduces plant growth and vigor. Rising sea level has the potential to increase flooding and reduce plant growth to the point that plants disappear. This rarely occurs at low rates of sea level rise because plants act as ecosystem engineers, raising the soil surface by trapping sediments in flood water and directly adding mass to the soil profile through root production (Kirwan and Megonigal 2013; Kirwan et al. 2016a). As these interactions raise the soil surface elevation, flooding depth and duration decline and approach the optimum for plant growth. Such plant-hydrology-geomorphology interactions are important at all scales and across all types of TAIs.

Landscape-Scale Processes and Dynamics

The fundamental processes that regulate exchanges across TAIs vary in predictable ways as spatial scales increase from pores to landscapes to catchments. In headwater systems, lateral exchange across TAIs is dominated by surficial features such as soil pore-size distribution, saturated flow in shallow groundwater, and hyporheic exchange rates. The dominant influence of runoff and shallow groundwater flow make headwater streams highly sensitive to spatial variation in land use (e.g., riparian forest, urban development, and agriculture). This happens because, as headwater streams coalesce into larger-order streams, their TAI processes tend to set the biogeochemical state of the larger drainage network (see Fig. 9, p. 24; Brinson 1993; Raymond et al. 2016). As stream order increases, the direct coupling of aquatic and terrestrial systems remains intact but declines in importance because of the increasingly large hydrologic and biogeochemical exchange with rivers through overbank flooding and deep groundwater (see Fig. 9, p. 24). Characteristics such as slope, soil parent materials, riparian vegetation, and other factors that influence headwater systems vary across hydrogeomorphic settings (e.g., coastal plains, piedmont, and mountains). These variations allow the scaling of biogeochemical processes using combinations of field sampling, geographic information systems (GIS), and remote sensing (Weller et al. 2011; Weller and Baker 2014).

A fundamental challenge to observing and modeling TAI processes is the physical dynamics of the systems. Migrating rivers, accreting floodplains, expanding and contracting wetlands and lakes, and evolving coastal regions all place TAIs in some of the most dynamic landforms on the planet. These changes occur at time scales of hours to centuries. Beyond inherent hydrologic variability, geomorphic changes fundamentally alter the physical structure of TAIs. In the terrestrial realm, river migration physically changes the location, length, and platform characteristics of rivers and reworks entire floodplains (see Fig. 10, p. 25), sometimes in as little time as a few decades. The physical exchange of sediment, organic material, and nutrients between floodplains and rivers resets both the sediment and biogeochemical composition of the system and alters the geomorphology of floodplains. Lakes and microtopographic features, such as scroll bars and terraces, are created, erased, and replaced.

Similarly, in coastal settings the erosion and deposition of landforms (e.g., deltas, tidal marshes, and barrier islands) strongly depend on long-term drivers (e.g., sea level rise and river discharges) and episodic storms that can both erode or deposit significant volumes of sediment. The building landforms serve as sinks for carbon and nutrients, while erosion leads to significant transfers of material from terrestrial to aquatic systems. The tight coupling of microtopography and hydrology strongly controls vegetation dynamics; therefore, the structural composition and patterns of vegetation succession are strongly regulated by the rate of landscape change (Hupp 1992). Conversely, vegetation strongly influences flows and sediment transport, thus exerting a direct feedback on the hydrologic, geomorphic, and microtopographic evolution of these systems (Camporeale et al. 2013; Gurnell 2014; Kirwan and Megonigal 2013). Human population pressure and use of these systems compound their sensitivity to natural change, demonstrating that land use is a major driver for landscape change (Pelletier et al. 2015).

Landscape-scale processes are inherently affected by changing extreme events. Flooding and low-flow conditions can cause inundation or desiccation that may be harmful or helpful, depending on the ecosystem component under consideration. For example, aquatic species may be forced into refugia in low-flow conditions, a state that stresses resources and leads to increased mortality if conditions prevail over long durations (Humphries and Baldwin 2003). High flows may lead to stress in terms of erosion and increased sedimentation and bed scour, removing or reducing quality habitats. Low flows particularly influence stream temperature and thus represent a major area requiring further study to understand the changing nature of hydroclimate regimes that may lead to exacerbated low-flow conditions (Kaushal et al. 2010).

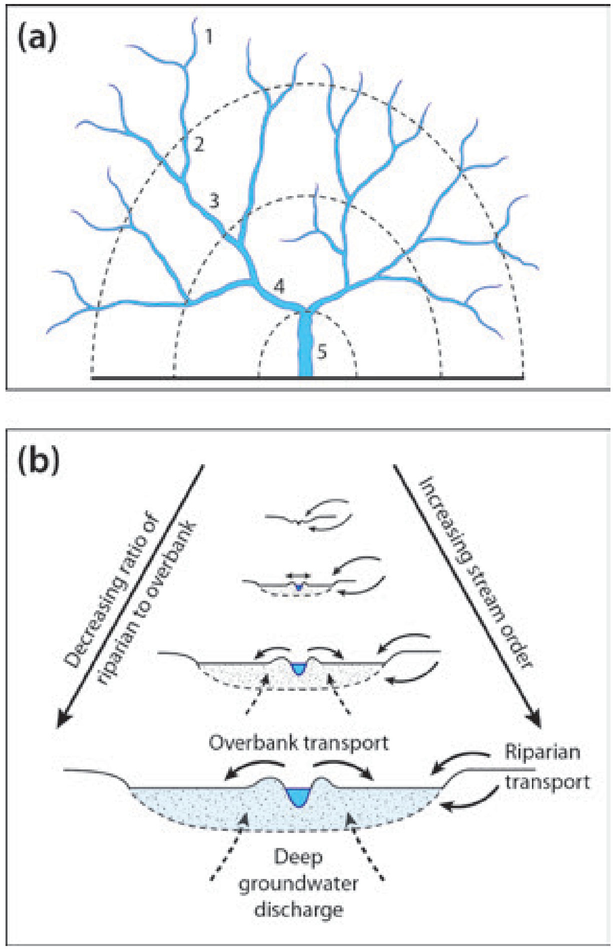


Fig. 9. Stream Order and Hydrology in Terrestrial-Aquatic Interfaces (TAIs). (a) Drainage network illustrating stream order and the decline in TAI density as stream size increases. **(b)** Changes in TAI hydrology with stream order. Surface and shallow groundwater (i.e., hyporheic) inputs are highest in low-order streams; overbank flooding and deep groundwater in high-order streams. [Modified and reprinted with permission from Springer from Brinson, M. M. 1993. "Changes in the Functioning of Wetlands Along Environmental Gradients," *Wetlands* **13**(2), 65–74. © Society of Wetland Scientists 1993]

Terrestrial-Aquatic Interface Processes Coupled to Streams and Rivers

Terrestrial-aquatic interfaces receive materials from upland terrestrial systems and process them to some extent before transporting them to open water systems. However, TAIs also are an original source of these materials, which they generate through plant, microbial, and physical processes and convey to aquatic

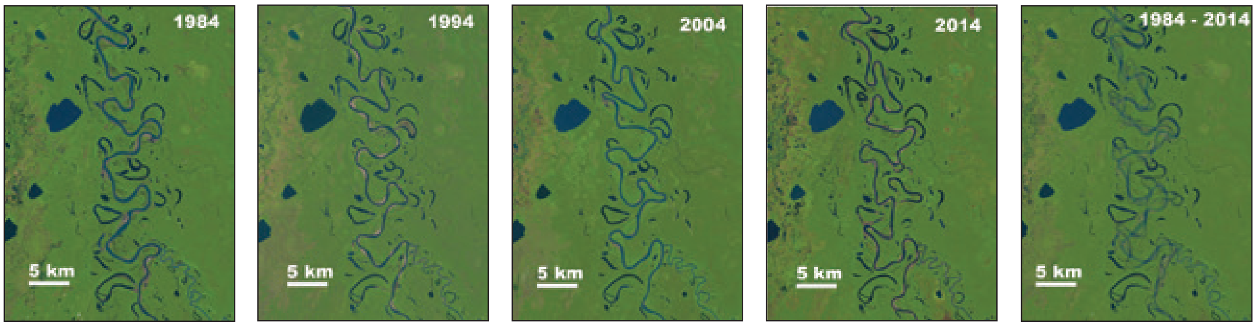


Fig. 10. South American River Migration: Landsat Images of the Mamore River in Bolivia. The first four panels (left to right) show 3 decades of river and floodplain change. The fifth panel shows all four images overlain to highlight the change in river location and floodplain. These images illustrate that the floodplains, river, and interface between them are highly dynamic. Rapidly evolving physical and natural systems are common in both inland and coastal terrestrial-aquatic interface settings and present unique challenges for observing and modeling these systems. [Images from 1984, 1994, and 2004 are from Landsat 5; 2014 image is from Landsat 8. Images courtesy U.S. Geological Survey]

systems. TAIs coupled to nontidal streams and rivers share a common set of processes by which they receive, transform, and convey materials, thereby affecting both TAIs and downstream aquatic systems.

Lateral Transport of Terrestrial Material

Temporal and spatial variations in hydrologic connectivity among terrestrial, TAI, and aquatic systems exercise significant control over aquatic biogeochemical cycles. Streams and rivers often flow in the absence of precipitation because of groundwater discharge (both deep and shallow) that provides a continual export of materials to aquatic food webs. However, materials also move into surface water during episodic events such as high-precipitation storm events or following major disturbances such as fire (Dahm et al. 2015; Raymond et al. 2016). Materials moving from terrestrial and TAI systems into streams are influenced by several factors including (1) local topography (e.g., through influences on erosion), (2) the structure of nearshore soils [e.g., thick organic layers providing more opportunity for leaching than mineral soils that sorb dissolved organic matter (DOM)], (3) precipitation dynamics (e.g., pulsed events that significantly increase discharge and transport terrestrial material via overland flow), and (4) hydrologic connectivity (e.g., less opportunity to transport terrestrial nutrients through subsurface flow in losing reaches).

Hyporheic zones represent a noteworthy example of hydrologic connectivity because they are entirely subsurface features (see Fig. 11, p. 26). Shallow groundwater carries terrestrially derived carbon, nitrogen, and phosphorous along flow paths that eventually intersect biogeochemically active shallow groundwater circulating through floodplains and river channels. Hyporheic flow can be the dominant transport mode for substrates that sustain microbial activity (e.g., CO_2 and CH_4 production and carbon storage as microbial biomass; Gomez-Velez et al. 2015; Harvey et al. 2013). A particle of water is estimated to enter the hyporheic zone eight times before it reaches a coastal ecosystem. The role of hyporheic zones in TAI biogeochemical cycles varies with landscape characteristics, environmental conditions, and climate. These zones account for about 80% to 100% of the CO_2 and nitrogen produced in wet-climate rivers and eventually released to the atmosphere as CO_2, but in dry climates like Mediterranean regions they are predominantly areas of carbon and nitrogen storage.

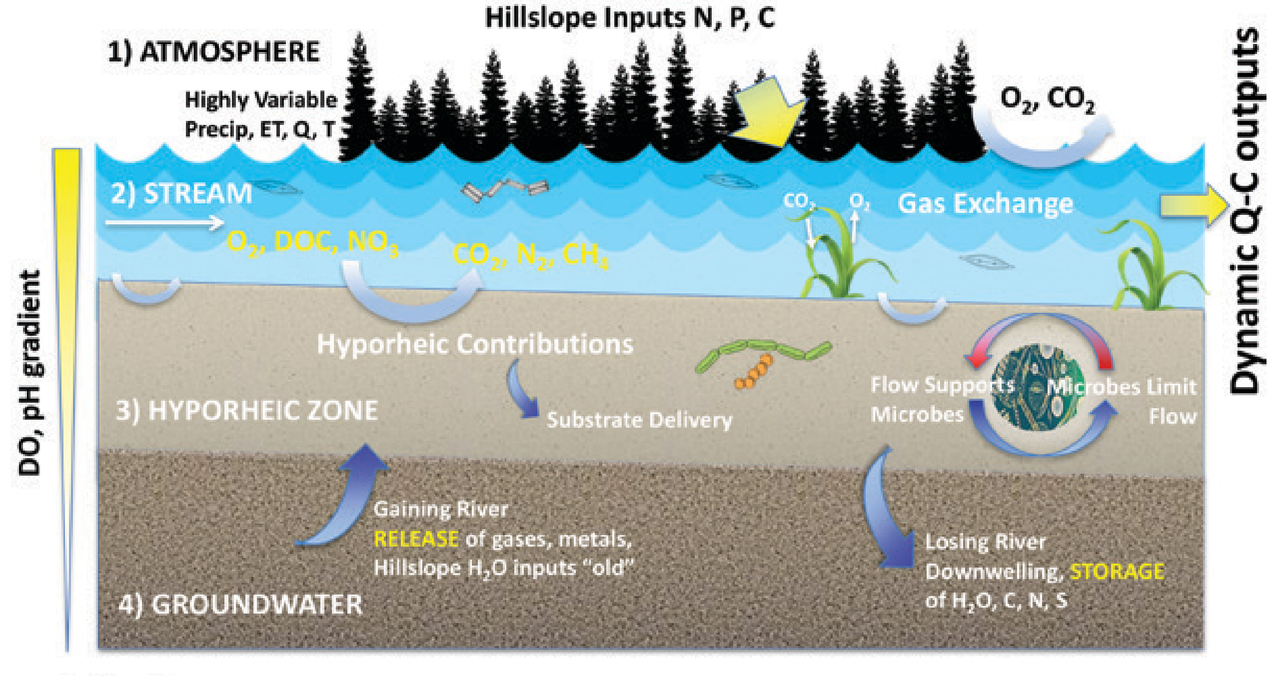


Fig. 11. Conceptual Model of the Compartments, Flows, Reactions, Feedbacks, and Pore-Scale Responses to Large Temporal and Spatial Terrestrial Inputs Within a Hyporheic Zone. The combination of these processes leads to large-scale responses in discharge, gas, and concentration measurements used as calibration and validation data for Earth system models at various points within the numerical grid. **Key: (1)** Atmosphere (zone of climate impacts). **(2)** Stream (mode of transport). **(3)** Hyporheic zone (zone of reactions). **(4)** Groundwater (zone of mixing with floodplain and hillslope; scales of meters and hours). Abbreviations: C, carbon; CH_4, methane; CO_2, carbon dioxide; DO, dissolved oxygen; DOC, dissolved organic carbon; ET, evapotranspiration; H_2O, water; NO_3, nitrate; N, nitrogen; O_2, oxygen; P, phosphorus; precip, precipitation; Q, streamflow discharge; S, sulfur; T, temperature. [Image courtesy Michelle Newcomer, Lawrence Berkeley National Laboratory]

The dominant role of hydrology and episodic events in transporting material through the terrestrial-aquatic continuum is highlighted by work showing that most carbon transport from the terrestrial system to surface waters can occur in just 18 days (Raymond and Saiers 2010). In addition, strong positive relationships exist between DOM concentrations and surface water discharge. Such patterns can emerge only if there is significant DOM accumulation in nearshore soils during periods of unsaturated conditions. DOM accumulates in soils in the absence of hydrologic connectivity between unsaturated soil and surface water until an episodic precipitation event establishes a hydrologic connection, transporting accumulated organic carbon across the TAI to surface water and downstream. Biotic and abiotic chemical transformations occurring in soils during periods of base flow tend to accumulate in soils until export (Bennett et al. 2001; Cai et al. 2013). Thus, terrestrial and TAI processes quantitatively affect aquatic biogeochemistry, rendering it sensitive to the timing and magnitude of precipitation events influenced by changing weather patterns and climate (Sebestyen et al. 2009). The flow portion that crosses TAIs through runoff versus shallow groundwater influences the extent to which soil processes, such as adsorption or desorption on mineral and organic surfaces, or microbial activities transform terrestrially derived materials.

Fate of Terrestrial Materials in Surface Water

The fate of materials derived from terrestrial and TAI ecosystems is relevant to modeling and understanding the biogeochemistry of TAI systems and downstream aquatic systems. There are four identified dominant fates of terrestrially derived materials once they enter surface water systems: (1) retention in the receiving aquatic system through deposition, sorption, or biological uptake; (2) transport and deposition to downstream aquatic systems; (3) transport and deposition in downstream TAIs; and (4) release to the atmosphere. The balance among these fates is strongly influenced by interactions among hydrology, geomorphology, and biology. Of particular relevance are hydrologic features such as groundwater flow paths, surface water connectivity with floodplains, hyporheic exchange with sediments, and water residence times in TAIs. The likelihood of material being transported to downstream systems depends partly on the rate at which surface water moves downstream, which in turn is controlled by topographic gradients, soil and sediment permeability, and hydrogeomorphic setting.

Residence time is an important parameter because it largely determines the efficiency of chemical and biological transformations of stream-transported materials. Riparian zones and floodplains are TAI features that slow water velocity; increase water residence time; and increase contact time between the transported materials and water, soils, plant communities, and microbial communities. Thus, riparian zones and floodplains are hot spots of sediment deposition and microbial activities that regulate important biogeochemical processes and transformations such as aerobic versus anaerobic respiration, denitrification, and methanogenesis. Residence time also is influenced by in-stream features that slow water by creating pools and eddies (e.g., coarse, woody debris) or drive surface water into hyporheic zone sediments. These physical features not only influence how quickly materials move downstream, they also control how materials interact with other system features such as temperature and light availability to influence the likelihood that terrestrially derived materials are eventually transported downstream versus being routed to other fates such as release to the atmosphere.

Terrestrially derived organic matter can be released to the atmosphere as biogenic gases—CO_2, CH_4, or nitrous oxide (N_2O). That is the outcome of a series of processes, with macroinvertebrates and microorganisms both playing key roles. Different groups of macroinvertebrates play different functional roles in the breakdown of terrestrial material in surface water systems. In particular, ”shredders” consume and break down coarse material (e.g., leaf litter), generating finer material for “collectors” that filter finer material from the water column. Both groups are heterotrophic sources of CO_2. However, while macroinvertebrates play a dominant role in organic matter breakdown, their direct contributions to biogenic gas emissions are small relative to those of microorganisms found in floodplain soils or hyporheic zone sediments.

In floodplains and hyporheic zone stream sediments, high rates of aerobic microbial respiration drive rapid conversion of terrestrially derived organic carbon to CO_2 where conditions favor high carbon inputs, high redox potentials, and high microbial activity (see Fig. 11, p. 26). In floodplains, such conditions occur in surface soil horizons because of high rates of plant carbon inputs, air (oxygen) exposure when soils are not flooded, and high densities of microbes associated with soil surfaces. In streams, aerobic respiration occurs as surface water recharges the hyporheic zone (e.g., incidences of undulating bedforms) for the same reasons. Sediment-associated microbiomes have more biomass and biogeochemical potential than planktonic microbiomes, whereas surface water can be enriched in oxygen and possibly carbon. Below the aerobic surface of floodplain soils and stream sediments, anaerobic metabolism dominates microbial metabolism because of the limited oxygen availability, favoring CO_2 emissions, coupled to dissimilatory metal and SO_4^{2-} respiration, or CH_4 and N_2O.

Whether the transported organic carbon is emitted as CO_2 versus CH_4 or used to support nitrogen cycling and N_2O production, it is strongly influenced by the residence time of surface water exchange with soils and sediments. In cases of short residence times, the dissolved oxygen entering soils may not be entirely consumed and aerobic respiration will yield CO_2 as the dominant biogenic gas. With longer residence times, oxygen depletion increases carbon flow through anaerobic metabolism. The specific pathways of terminal microbial respiration depend critically on the supply of terminal electron acceptors. For example, a supply of NO_3, iron minerals, or SO_4^{2-} may enable denitrification and eventual N_2O production or CO_2 production coupled to iron or SO_4^{2-} reduction, respectively. With long residence times or lack of alternative electron acceptors, methanogenesis becomes the dominant pathway of microbial metabolism, routing terrestrially derived organic carbon to the atmosphere as CH_4. The degree to which terrestrial material is routed to the atmosphere as biogenic gas (and in which chemical form) is the result of the complex interplay among physical, biological, and chemical features (Megonigal et al. 2003). These interactions must be captured in models aimed at predicting the response of the terrestrial-aquatic continuum to environmental change.

Terrestrial material may be retained in the receiving aquatic system through sorption onto mineral surfaces and physical burial, although deposition and burial are more likely to occur in downstream systems such as floodplains or pools created by natural or anthropogenic (e.g., dam) features (Ran et al. 2014). The degree to which sorption occurs depends on the magnitude of hydrologic exchange between surface water and soils or sediments, as well as their mineralogy. Hydrogeomorphic features that enhance exchange with floodplains or hyporheic exchange inherently increase the opportunity for sorption, and the high surface area and negative charge of clay minerals likewise increase the opportunity for sorption. There are important interactions among these phenomena, however, whereby higher clay content can enhance sorption but also can decrease hydrologic exchange by decreasing sediment permeability. Capturing such potentially nonmonotonic effects is critical for their representation in predictive models, especially those models that simulate landscape evolutionary processes that alter the hydrogeomorphic character of TAIs associated with streams and rivers.

In addition to organic matter and eroded soil, terrestrial systems deliver inorganic nutrients to surface water systems. These inorganic nutrients can be used to support autotrophic production in both aboveground and belowground domains. Supplied nutrients also are used to fuel heterotrophic metabolisms. The ability of in-stream primary producers such as periphyton, phytoplankton, and submerged macrophytes to use dissolved nutrients depends largely on light availability, which varies across stream orders. In many low-order headwater streams, there is relatively little light penetration through the riparian canopy, and nutrients are transported downstream to higher-order streams with greater light availability.

Lateral Exchange with Floodplains

Many TAI systems are created by water bodies, and they expand, flow, and contract over terrestrial systems. Streams and rivers create riparian zones and floodplains with which they continually exchange water, sediment, and geochemical constituents. As with other TAIs, floodplains are manifested across very large spatial and temporal scales that change predictably with stream order, ranging in width from tens to thousands of meters and in lengths up to thousands of kilometers. As river-floodplain dimensions change, so do the dominant time scales and hydrogeomorphic processes over which they exchange materials.

The dynamic interactions and lateral exchanges of materials characteristic of floodplain systems make incorporating floodplains into ESMs a unique challenge. Accurate forecasts of terrestrial, hydrological, and element-cycle dynamics and fluxes to estuaries, inland seas, and coastal oceans are not possible without

capturing the dynamics of floodplain exchange. For example, two large tropical river systems highlight the magnitude of exchanges between floodplain and river channels. First, on the Fly River in Papua New Guinea, up to 40% of the river flow and sediment load is transferred during flood events onto the floodplain; even though much of the water returns to the river, the majority of sediment is deposited on the floodplain (Day et al. 2008a, b). Second, along the central Amazon River a greater mass of sediment (150%) is exchanged with the floodplain than is transported by the river to the ocean (Dunne et al. 1998), and at least 30% to 40% of river discharge is routed through the floodplain on the way to the ocean (Wilson et al. 2007).

Floodplain plant communities range widely in structure, functional groups, and species diversity. Plant communities can be dominated by floating aquatic vegetation or emergent species that are herbaceous plants, woody shrubs, or trees. The morphological and physiological traits of plant communities are critical features that contribute to hot spots and hot moments of biogeochemical activities. Stream order, geomorphic setting, and climate strongly influence the development of floodplain plant communities. Of particular importance are the magnitude, frequency, and duration of flood events because tolerance of flood stress largely determines the establishment and growth of plant species. Plant communities on floodplains typically are arrayed on lateral, longitudinal, and vertical gradients that reflect differences between land-surface elevation and water elevation and dynamics (Bunn and Arthington 2002). Plant species also respond to spatial and temporal variation in soils, climate, and ecological factors such as interspecies competition known to generally influence plant community composition across environmental gradients (Whittaker 1970; Naiman et al. 2005; Saintilan and Rogers 2015).

Plant species composition, community structure, and productivity control key aspects of floodplain biogeochemistry. Plant establishments stabilize floodplain sediment deposits and the pace of geomorphic processes such as channel evolution (Hupp 1992; Camporeale et al. 2013; Gurnell 2014). By reducing the velocity of floodwater, plants enhance sediment deposition rates and thereby contribute to the role of floodplain systems as hot spots of nitrogen, phosphorus, and carbon deposition and storage (Noe and Hupp 2009).

Estuaries and Coasts

The fundamental Earth system processes that operate in TAIs coupled to streams and rivers also operate in tidally dominated landscapes characterized by estuaries and coasts, but ocean and near-shore physics impose distinct differences in the hydrodynamics, geomorphology, and biogeochemistry that influence these TAI dynamics. The mixing of freshwater and saltwater imparts dramatic changes in aquatic chemistry, producing a three-dimensional water column stratification that varies on diel, tidal, seasonal, and longer time scales, the influences of which often extend farther upriver than the direct influence of salt (Hoitink and Jay 2016). TAIs coupled to tidal rivers (e.g., freshwater, brackish water, and saltwater), estuaries, and coasts are controlled by complex interactions among hydrodynamic forces, engineering of natural and human-made systems, and organisms that build habitats such as tidal marshes, mangroves, and seagrass meadows. These biogeochemical hot spots are where estuaries, coastal wetlands, and the adjacent coastal ocean connect with each other, as well as with human populations and their activities.

Traditionally, estuarine science defines the maximum landward extent of salt in water (brackish water) as the upper boundary of the estuary or lower boundary of the river. River reaches that are tidal but freshwater (i.e., salinity <0.5 practical salinity units) are termed "freshwater tidal rivers," which extend to the "head of tides," another important location within coastal rivers. Above the head of tides, the physical processes in a river are described by principles and methods traditionally applied to the study of watersheds. Below the head of tides, principles and methods from oceanography must be integrated to adequately understand

and describe the system. The length and breadth of the freshwater tidal river between the estuary and the head of tides range from nonexistent to hundreds of kilometers long and tens of kilometers wide in large, low-gradient rivers such as the Columbia, Mississippi, and Yangtze. In such tidal river reaches, the physical processes may or may not be reasonably well described using fluvial methods, depending on the relative dominance of river discharge and ocean conditions.

Estuaries and coastlines are strongly affected by increases or changes in extreme conditions. For example, interactions among rising sea levels, heavy precipitation, and high tides may lead to strong increases in coastal erosion. Extreme events such as hurricanes and cyclones may cause damage to important TAIs such as mangrove forests and lead to deterioration of these features and reduction in their ability to buffer the coastline and its associated ecosystem from consecutive storm events. The increase in these events is documented and is an integral component of understanding how TAIs will be altered under environmental and climate regimes (IPCC 2012).

Fate of Terrestrial and Aquatic Materials in Estuaries

Terrestrial-aquatic interfaces and their processes represent an important component of the coastal landscape and play a significant role in linking terrestrial and ocean systems (Regnier et al. 2013; Canuel and Hardison 2016). Nontidal rivers that enter estuaries carry the imprint of both TAI and aquatic processes that occurred upstream, which include dissolved and particulate forms of organic and inorganic carbon and nutrients, suspended sediments, and pollutants (Bianchi 2006). Dramatic changes in aquatic geochemistry occur downstream of the estuarine TAI region because the mixing of freshwater and saltwater drives repeated cycles of sedimentation and resuspension throughout tidal cycling. The resultant zone has very high turbidity—the "estuarine turbidity maximum"—characterized by intense processing of organic matter, oscillating redox conditions, oxygen depletion, and enhanced exchange of materials between the dissolved and particulate phases (Abril et al. 1999). These processes promote biotic and abiotic (photochemical) transformations of organic matter that are important for aquatic biogeochemistry (Komada and Reimers 2001; Middelburg and Herman 2007) and estuarine TAIs (see Fig. 12, p. 31). For example, tidal marshes are known to exhibit dramatically higher sediment deposition rates in the zone of estuarine turbidity maximum (Darke and Megonigal 2003), a condition that makes these marshes relatively resilient to accelerated sea level rise compared to tidal wetlands outside this zone. The position of the estuarine turbidity maximum changes with river discharge and sea level, and modeling this feature is important to forecasting tidal marsh responses to global climate and other environmental changes.

Lateral Exchange with Intertidal Wetlands

Intertidal wetland interactions with aquatic and terrestrial systems are similar to those of riparian zones and floodplain TAIs with nontidal streams and rivers (see Fig. 13, p. 32). These wetlands cycle through periods of soil inundation and exposure, supporting plant communities composed of the same functional groups such as grasses, shrubs, and trees. As in floodplains, vegetation slows the velocity of floodwater, thereby enhancing sediment deposition and bringing estuarine water in contact with an active soil microbiome that drives rapid biogeochemical transformations. Intertidal wetlands can act as both sources and sinks of solids and solutes. Typically, they are sinks of suspended sediments and particulate matter (Nixon 1980; Childers et al. 2000; Tzortziou et al. 2011) and sources of dissolved inorganic carbon (DIC), DOM, and colored dissolved organic matter (CDOM) to estuaries and coastal oceans (Cai 2011; Tzortziou et al. 2008).

Tidal marshes are known to be strong sources of dissolved organic carbon and CDOM for their adjacent waters (Childers et al. 2000; Tzortziou et al. 2008), affecting estuarine optics, biogeochemistry, and

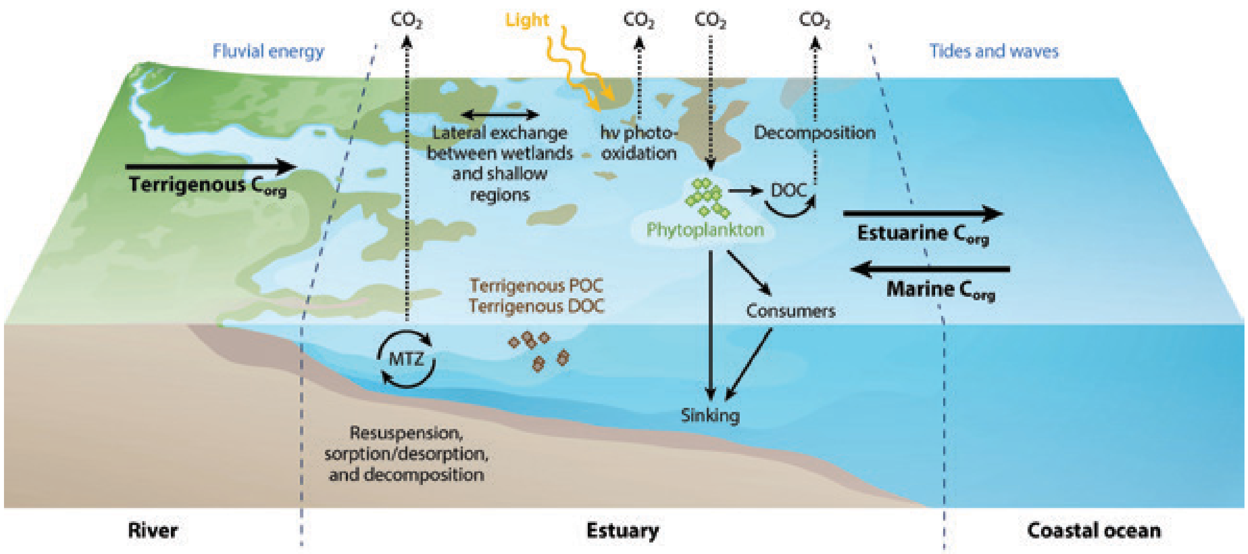


Fig. 12. Sites of Organic Matter Sources and Exchange Along the River–Estuary–Coastal Ocean Salinity Gradient. Shown are the dominant sources of energy at the end members of the river (fluvial) and ocean (tides and waves). A variety of processes—abiotic (e.g., photochemical oxidation, sorption/desorption, sinking, and burial) and biotic (e.g., microbial decomposition, phytoplankton production, production in photic shallow environments, and uptake into consumer organisms) influence the fate of organic matter. Abbreviations: C_{org}, organic carbon; CO_2, carbon dioxide; DOC, dissolved organic carbon; MTZ, maximum turbidity zone; POC, particulate organic carbon. [Reprinted with permission from Canuel, E. A., and A. K. Hardison. 2016. "Sources, Ages, and Alteration of Organic Matter in Estuaries," *Annual Review of Marine Science* **8**, 409–34.]

photochemistry considerably beyond the marsh-estuary interface (Hermann et al. 2015). Based on an upscaling of a detailed regional budget for marshes in the southeastern United States (Cai 2011), a conservative estimate of the annual global export of organic carbon from marshes to the outer shelf, and possibly the open ocean, is 174 to 400 Tg C y^{-1}; however, much higher fluxes from wetlands to the coastal ocean have been reported (Duarte et al. 2005; Regnier et al. 2013). This is indeed a significant contribution compared with the annual global flux of riverine organic carbon (460 Tg C y^{-1}) or the burial rate of oceanic organic carbon (120 to 220 Tg C y^{-1}). Although highly susceptible to photochemical degradation (Tzortziou et al. 2007), coastal wetland–derived DOM is transported laterally as far as the nearshore continental shelf and slope waters where it enhances secondary production (Bianchi and Argyrou 1997).

Evidence is mounting that tidal wetlands are dominant sources of DIC to coastal waters (Smith and Hollibaugh 1993; Frankignoulle et al. 1998). All plant respiration and most forms of microbial respiration (other than CH_4 production) in soils and sediments generate DIC in the form of CO_2, bicarbonate, or carbonate according to pH. Carbon budgets suggest that tidal marshes and mangroves export >10% of their net primary productivity as DIC (Neubauer and Anderson 2003; Sippo et al. 2016; Wang et al. 2016). In one estimate, tidal marsh DIC exports were estimated to explain 47% of excess water column DIC (Raymond et al. 2000; Neubauer and Anderson 2003). Cai and Wang (1998) demonstrated that almost all CO_2

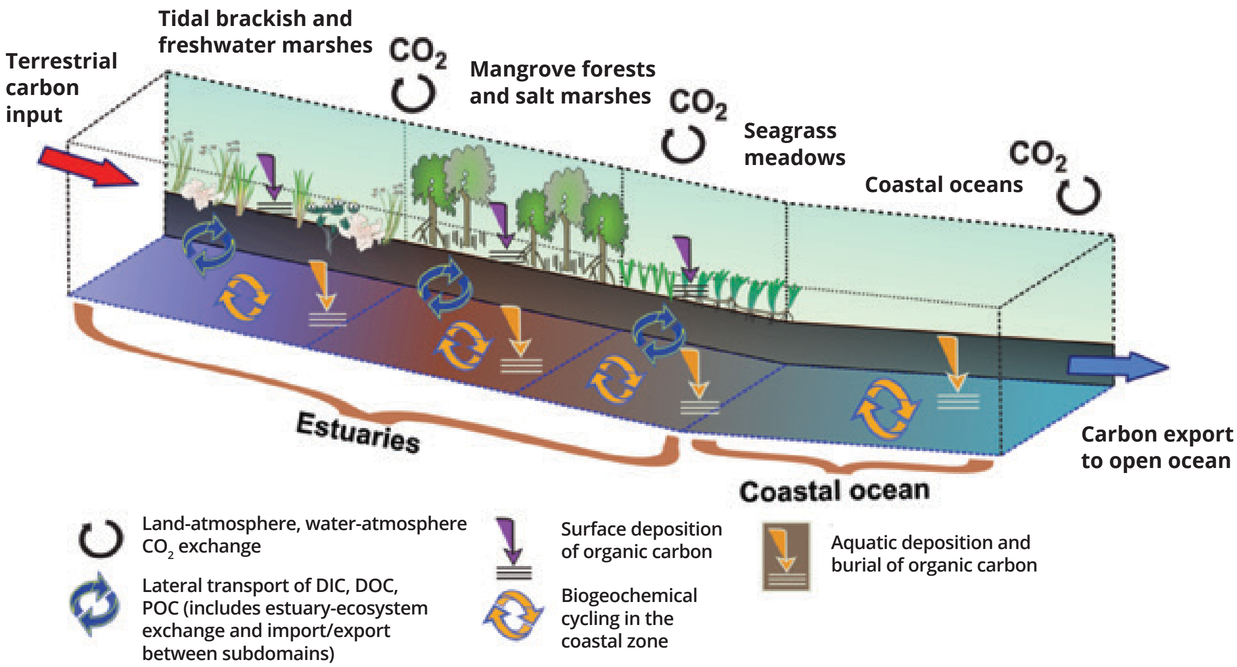


Fig. 13. Conceptual Model of Coastal Carbon Cycling. This model includes tidal brackish and freshwater marshes, mangrove forests, saltwater marshes, and seagrass meadows and comprises estuaries and the coastal ocean. Abbreviations: CO_2, carbon dioxide; DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; POC, particulate organic carbon. [Image courtesy Jordan Barr. In: Troxler, T. G., et al. (in review). "Carbon Cycles in the Florida Coastal Everglades Socio-Ecological System Across Scales," *The Coastal Everglades: The Dynamics of Socio-Ecological Transformation in the South Florida Landscape*. Eds. D. Childers, E. Gaiser, and L. Ogden.]

degassing in the Satilla River estuary is supported by lateral carbon transport from intertidal salt marshes and that CO_2 loss to the atmosphere exceeds the river DIC flux by tenfold.

Regular tidal flooding and sea level rise result in unusually rapid rates of soil organic carbon sequestration and large carbon pools in tidal wetlands and seagrass beds compared to nontidal floodplain TAIs (Bridgham et al. 2006; Donato et al. 2011; Fourqurean et al. 2012). Although tidal wetlands occupy an area equivalent to just 2% of the ocean surface, they account for 50% of the carbon in marine soils and sediments (Mcleod et al. 2011; Hopkinson et al. 2012). Large-scale disturbance of coastal wetlands contributes to climate forcing (Pendleton et al. 2012).

Hydrogeomorphic Processes at the Terrestrial-Aquatic Interface in Estuaries and Coasts

Hydrology is a master variable that regulates exchanges between terrestrial and aquatic systems across TAIs. Of particular importance is the two-way interaction between hydrology and geomorphology that shapes TAI ecology and biogeochemistry at all scales. While this perspective applies to all TAIs, it is arguably most important in estuaries and coasts where hydrology, geomorphology, and biology interact in ways that make TAIs highly dynamic over short temporal and spatial scales, ultimately determining the presence or absence of tidal wetlands.

The dynamics of an individual TAI are constrained by the geomorphic setting and vary considerably across estuaries, open coasts, barrier systems, and other large landforms, each of which adjusts to changes in the balance between wave energy (including long waves such as tides) and the distribution of sediment. Spatial and temporal variations in sediment supply, wave energy, tidal range, geomorphic setting (e.g., river delta, carbonate platform, and active margin), and historical rates of sea level rise largely control the distribution of intertidal and subtidal habitats. Ultimately, these variations also control carbon sequestration in coastal sediments, much of which is terrestrially derived (Blair and Aller 2012).

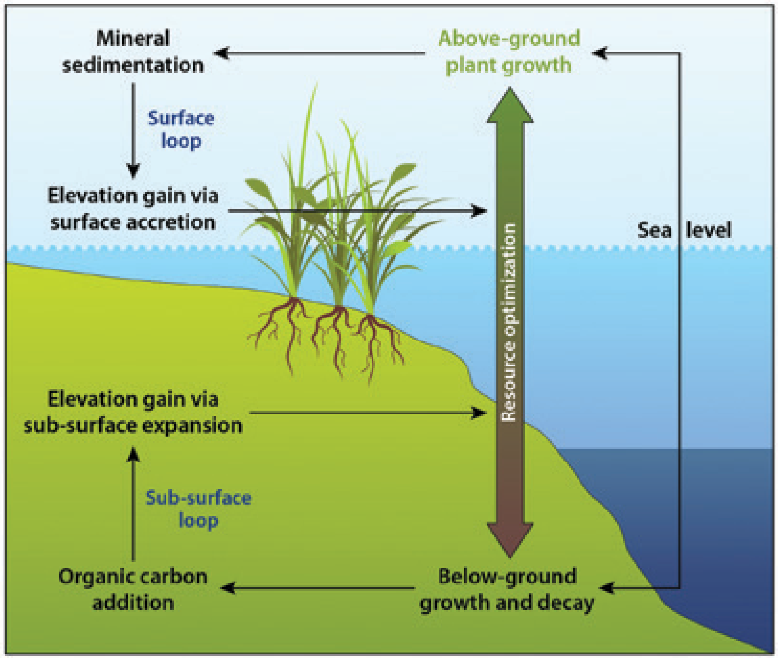
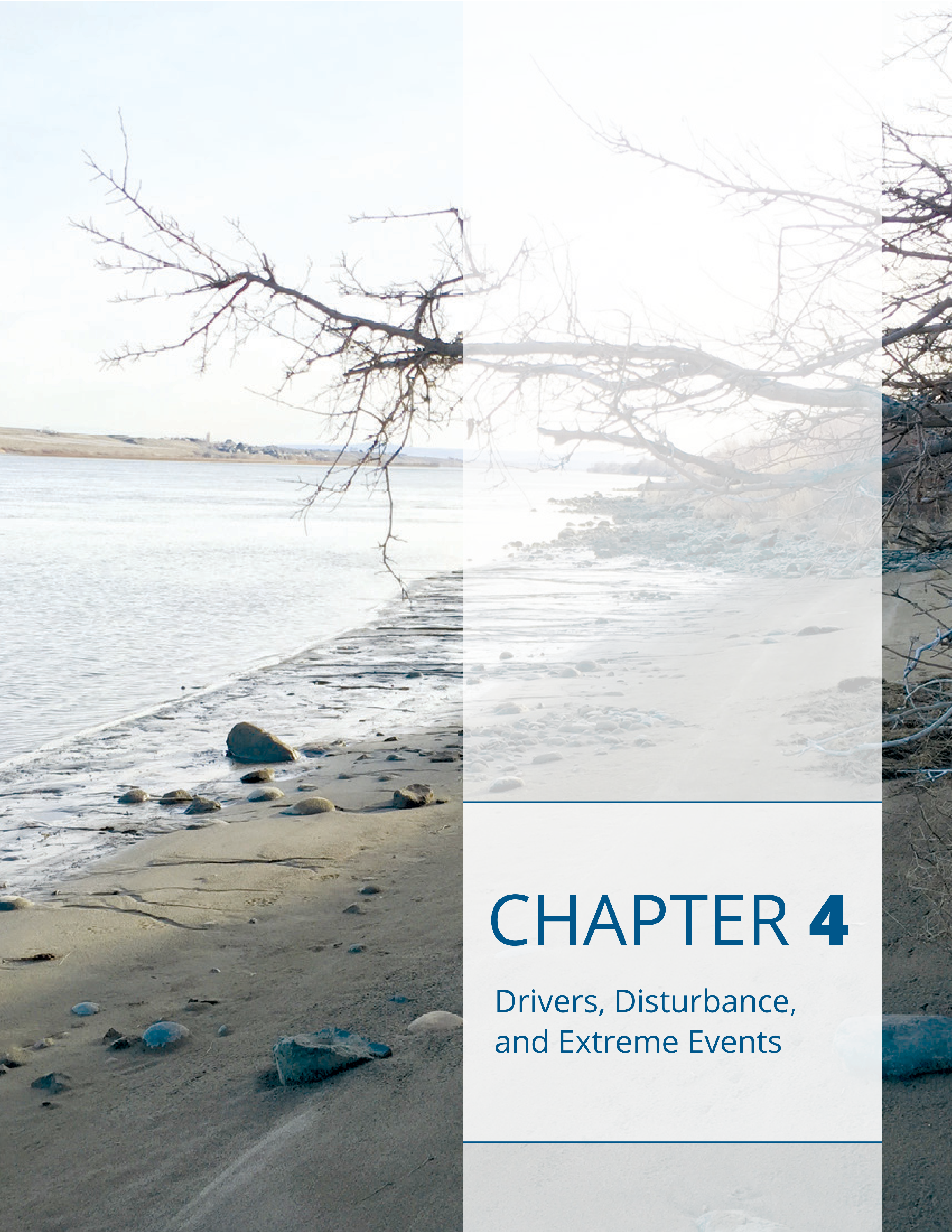


Fig. 14. Ecohydrogeomorphic Feedbacks that Regulate Elevation Gain and Carbon Sequestration in Tidal Marshes. [Reprinted by permission from Macmillan Publishers Ltd.: Kirwan, L., and J. P. Megonigal. 2013. "Tidal Wetland Stability in the Face of Human Impacts and Sea-Level Rise," *Nature* **504**, 53–60. © 2013]

Vascular plants influence coastal hydrogeomorphology through feedbacks that stabilize them against long-term changes such as sea level rise and episodic events such as storm surge erosion (see Fig. 14, this page). These feedbacks operate by two fundamentally different mechanisms that correspond to aboveground plant traits versus belowground traits. Sediment deposition on soil surfaces increases in plant surface area, allowing plants to build elevation from the surface upward at rates that ultimately are limited by the local sediment supply (Kirwan and Megonigal 2013). Belowground plant production builds elevation from underneath the soil surface by depositing organic matter directly into the anaerobic soil profile where it is efficiently preserved compared to aboveground plant production. Belowground production is critical to the stability of tidal wetlands where sea level rise is accelerating, because this production contributes about four times more elevation than an equal mass of inorganic sediment (i.e., silt or clay). However, microbial decomposition causes SOM to be more prone to loss than inorganic sediment. As such, a critical need is to understand the biogeochemical conditions that regulate decomposition in tidal wetland soils.

A large fraction (perhaps up to 10%) of plant-derived organic matter is recalcitrant to decay in the absence of oxygen, the overwhelming agent of preservation in saturated soils and sediments. The molecular composition of plant tissue is an important secondary factor, but many mechanisms for organic matter preservation in uplands (Schmidt et al. 2011) are not important in wetlands. Organic matter preserved in marsh, mangrove, and seagrass soils is sensitive to changes in plant production (Mueller et al. 2016) and salinity (Craft 2007), among other factors.



CHAPTER 4

Drivers, Disturbance, and Extreme Events

4

Drivers, Disturbance, and Extreme Events

Terrestrial-aquatic interface (TAI) systems, inherently dynamic in space and time, are subject to dramatic changes in structure and function in response to external forcing. TAIs are often defined by events such as flooding that occur so regularly that they constitute a regime to which organisms are highly adapted and that cannot be interrupted without fundamentally changing the system. Other events are rare but critical for the long-term maintenance of ecosystem structure and function because they disrupt this short-term stability, thus maximizing long-term stability and creating a paradox in which the absence of disturbance makes the system vulnerable to degradation (Johnstone et al. 2016). Finally, some disturbances are so dramatic that they directly degrade TAI systems (e.g., land-use change). As with terrestrial systems, carbon flux in TAIs following disturbances is expected to follow a conceptual trajectory with an immediate loss of carbon following a disturbance and subsequent recovery to either predisturbance carbon fixation rate or conversion to another ecosystem state. Carbon loss following disturbances such as fire, harvest removals, insect outbreaks, and coastal storms is the result of vegetation death, biomass combustion, and vegetation loss that alter primary productivity and ecosystem respiration (Amiro et al. 2010). TAI systems also have very large soil carbon stocks that are susceptible to disturbances, particularly in peat-forming TAIs where plant production and slow, anaerobic decomposition are primary drivers of soil carbon accumulation (Pendleton et al. 2012). This section discusses the unique characteristics of TAIs that make them highly sensitive to external agents of change.

Hydrologic Disturbance

TAIs are defined by characteristic hydrologic dynamics that give rise to hot spots and hot moments of biogeochemical activity. As such, changes in hydrology are frequently the drivers of change in TAI systems. TAIs differ from other ecosystem types in that relatively subtle changes in hydrologic conditions cause dramatic impacts.

Climate-Driven Hydrologic Change

Changing climate is a major agent of hydrologic change capable of altering TAI processes (Hulme 2005; Erwin 2008). Indeed, hydrology is a key reason that TAIs such as wetlands are among the ecosystems most vulnerable to climate change (Burkett and Kusler 2000; Winter 2000; Ferrati et al. 2005; Erwin 2008). Precipitation and evapotranspiration are important drivers of hydrology and thus soil carbon flux and soil organic carbon (SOC) content; soils tend to shift from net carbon uptake to carbon loss when conditions become drier. For example, the south Florida Everglades is a landscape-scale TAI system in which climate-driven changes in hydrology may have significant impacts (Obeysekera et al. 2011a). Some models project an annual increase in precipitation of up to 14% (IPCC 2013), but a decrease by up to 10% during the wet season (Christensen et al. 2007). This combination of lower wet season and higher dry season precipitation suggests overall less seasonality. However, uncertainties in model projections call for scenario-based approaches (Obeysekera et al. 2011b, 2015). Such climate-driven changes can result in broad-scale changes and feedbacks to plant community

composition; primary production; and export of freshwater, carbon, and nutrients to estuaries. Numerous examples exist that illustrate the profound influence of precipitation extremes on flood extent in wetland landscapes (i.e., Rouillard et al. 2015). However, the influence of flood extent resulting from drought and inundation events on wetland function varies significantly with wetland type and biogeochemical conditions, management history, and climate (Brigham et al. 1998; Venterink et al. 2002).

Changes in precipitation resulting in extreme events such as drought also have significant impacts on carbon dioxide (CO_2) exchange and carbon flux from soils. Drought can result in severe disturbance to peat-forming TAIs. Even short-duration drought can be conducive to accelerated rates of soil oxidation and decomposition at the exposed peat surface and can introduce the potential for peat fires. An El Niño event resulted in altered freshwater-marsh CO_2 exchange rates with the atmosphere (Malone et al. 2014), a change consistent with experimental simulation of drought (Malone et al. 2013). Climate and environmental changes may increase the frequency or severity of drought events, and drought intensity was projected to result in wetlands converting to carbon sources across the United States (Chen et al. 2012). However, acute die-off has been attributed not only to drought-induced phenomena, but also to changes in soil chemistry, environmental pathogens, herbivory, and other stressors (McKee et al. 2004; Alber et al. 2008).

Changes in climate also are projected to result in larger convective storms and more intense hurricanes (Allan and Soden 2008). Hurricane disturbance results in significant CO_2 flux to the atmosphere associated with defoliation, vegetation die-off, and increased exposure of soils to solar radiation; however, canopy structure and CO_2 fluxes can recover fairly rapidly (Barr et al. 2012). When hydrologic patterns are altered, extreme storms can hinder recovery. In the coastal region of Louisiana, construction of flood-control levees, oil and gas canals, and roads through wetland areas have greatly altered hydrologic patterns over the past hundred years, resulting in major changes to the natural hydrologic regimes (Conner et al. 1981; Day et al. 2007). Sediment deposition has been altered and subsequent wetland accretion modified. In combination with regional land subsidence, these changes have led to increased flooding (Conner et al. 1993). The effects of hurricane disturbances in this region vary depending on storm intensity and the extent of legacy hydrologic alterations (Conner et al. 2014). Furthermore, in coastal marshes of southwest Florida, observed disturbances from hurricanes and fire, along with saltwater intrusion, resulted in the conversion of peat marsh to open water (Wanless and Vlaswinkel 2005).

TAIs are highly sensitive to climate and environmental changes that influence variability in temperature (Winter 2000). Temperature extremes such as frosts and heat waves have contributed significantly to changes in TAIs, including the chilling damage observed in subtropical south Florida that resulted in major vegetation die-off of mangrove trees (Ross et al. 2009). Also observed have been low-temperature events altering CO_2 exchange with the atmosphere in subtropical TAIs (Malone et al. 2016). In coastal mangrove forests, the presence of hypersaline conditions and high solar irradiance loading associated with climate variability can impose sharp reductions in carbon assimilation rates and suppress stomatal conductance (Barr et al. 2009), resulting in strong feedbacks with biogeochemical cycling and atmospheric CO_2 emissions.

One of the most certain and severe consequences of a warming climate is the acceleration of sea level rise through land ice sheet melt and thermal expansion of ocean water (IPCC 2013). Accelerating sea level rise is a global perturbation affecting nearly all coastal TAIs. Water level relative to sediment surface is the dominant factor driving coastal zonation; thus, changes in water level will have dramatic impacts on coastal TAI boundaries in vertical and horizontal dimensions. Both tidal and coastal nontidal wetlands have some capacity for building vertically through soil development, thereby maintaining a constant elevation relative to sea level (Nyman et al. 2006;

McKee 2011; Lentz et al. 2016). However, this building is heavily dependent on hydrogeomorphic, biogeochemical, and productivity feedbacks that will be altered by climate and environmental changes. In particular, plant productivity and microbial processes respond to changes in inundation frequency, elevated CO_2, and salinity, all of which can influence elevation gain or loss, as these processes exert feedbacks to soil elevation (Pezeshki et al. 1990; Cahoon et al. 2003). While small-scale models have begun to represent such processes and their influence on coastal elevation dynamics, they have not yet been extrapolated to the global scale. There remain many uncertainties such as plant tolerance for flooding (Langley et al. 2013) and interactions with multiple climate change factors. Salt water intrusion can increase carbon loss from coastal TAIs by triggering a short-term reduction in plant growth while stimulating heterotrophic respiration rates (Herbert et al. 2015).

Rising sea level can cause coastal wetlands to migrate horizontally onto uplands where conditions permit (Kirwan et al. 2016b). Many coastal areas at least have some capacity to adjust dynamically to rising seas. In some cases, coastal ecosystems can migrate horizontally, provided that inland landforms are suitable, and increase soil carbon stocks. For example, mangroves are migrating poleward to overtake marshes in subtropical regions all around the world because of declining freeze frequencies (Saintilan et al. 2014). Such a conversion from TAI herbaceous grasslands to TAI forests greatly increases carbon uptake on the landscape scale (Doughty et al. 2016). Coastal development can hinder the ability of these TAI ecosystems to migrate. The most obvious example is the hardening of shorelines by construction of concrete seawalls and jetties that commonly occurs along with dense coastal development. Currently, 14% of the U.S. coastline has been hardened, with a great likelihood of increasing future armament (Gittman et al. 2015). These structures often preclude the horizontal migration of coastal wetlands, ultimately exacerbating coastal wetland loss.

Human Impacts on Hydrology

Terrestrial-aquatic interfaces are highly sensitive to hydrologic modifications that increase their vulnerability to other forms of disturbances (Nelson et al. 2008), with potential for nonlinear feedbacks and threshold exceedances (Herbert et al. 2015). Over a century of water management and hydrologic modification in TAIs has dramatically altered wetlands across the United States, with the Florida Everglades being a prime example (Light and Dineen 1994; Davis et al. 2005). The construction of roads, canals, levees, and flow-control structures has modified the quantity, quality, timing, and location of water delivery to the Everglades. These changes have altered hydroperiods, salinity and nutrient levels, community assemblages, fire regimes, and ultimately carbon cycles and storage (Snyder and Davidson 1994; McCormick et al. 2001; Gaiser et al. 2006).

Agricultural drainage contributes to a persistent release of CO_2 from TAIs previously under saturated conditions. Drainage can cause the loss of several meters of organic peat soil, depending on its depth (Hirano et al. 2012; Hooijer et al. 2012). To sustain agricultural production, drainage depth is continually drawn down, resulting in persistent carbon loss until soil carbon stocks are exhausted (Gleason and Stone 1994; McVoy et al. 2011). For example, Aich et al. (2013) and Hohner and Drecshel (2015) suggest that 7.6 to 9.2 × 10^8 megagrams of peat soil carbon have been lost from the Everglades Protection Area (i.e., the Everglades Agricultural Area Water Conservation Areas and parts of the freshwater Everglades National Park) over roughly the last 120 years. The increasing vulnerability of peatlands to combustion in response to drying and reduced precipitation in some regions exposed to climate change and human activities likely will continue in coming decades (Turetsky et al. 2017). Human activities, which have concentrated in and around rivers and estuaries for millennia, have modified TAI processes through dredging, straightening, mining, and other uses (Nilsson et al. 2005). Moreover, river flow that generally prevents long residence times is

interrupted by reservoirs created for water management that trap sediment and organic matter and create enhanced methane (CH_4) emissions (Guérin et al. 2006). Rapid expansion of hydropower in Asia and South America is adding reservoirs at an increasing pace. By altering processes in TAIs, human activities contribute to eutrophication and impacts from climate and environmental changes on aquatic systems, such as water column stratification, warming effects on metabolism, shifts in aquatic species distributions, and deoxygenation (Canuel et al. 2012).

Coastal zones constitute 2% of the world's land area, but they contain 10% of the world's population (600 million), 13% of the world's urban population (360 million), and about 65% of the world's cities with populations greater than 5 million (McGranahan et al. 2007). Typical human activities in the coastal zone cause changes in sediment dynamics, increased loading of nutrients to coastal wetlands, and conversion of coastal wetlands to open water and reclaimed land, with significant consequences for carbon sequestration and transport. Coastal wetlands, such as mangrove forests, tidal marshes, and seagrasses, comprise a TAI set that has been intensively modified by anthropogenic activities through hydrologic alterations such as draining, filling, diking, and impoundment. Consequences of such activities include the rapid conversion of mangroves to shrimp ponds and fish farms through hydrologic alteration, which leads to substantial carbon emissions to the atmosphere (Pendelton et al. 2012). Often the farms are abandoned after several years of cultivation because without plants to resist erosion and build soil, the ecosystem converts to open ocean with a subsequent loss of the carbon sequestration previously provided by the mangrove forests. Ultimately, this process results not only in loss of forests, but also in loss of land area. Other practices drain tidal marshes for agriculture, dike them to separate marsh from tides, fill the area with imported sediment, and extract soil to construct ponds for salt production.

Estuarine aquatic systems are sensitive to disturbances. The effects of climate and environmental changes, such as sea level rise and altered precipitation patterns, influence the hydrogeomorphic processes that regulate fluxes of freshwater, sediment, nutrients, and carbon (Najjar et al. 2010; Cloern et al. 2011). Cloern and Jassby (2012) identified six primary drivers of change in coastal-estuarine processes: water consumption and diversion, human modification of sediment supply, introduction of nonnative species, sewage input, environmental policy, and environmental and climate shifts. Identifying universal trends across the systems is made difficult by the varying strengths of these drivers and their interactions across estuaries. Human population pressures near waterways and coastlines dictate that TAIs are necessarily susceptible to acute human disturbances that create or eliminate these systems (Donchyts et al. 2016). Coastal development remains the greatest threat to wetlands.

Accelerating sea level rise, along with other factors such as freshwater diversions, will shift the boundaries of tidal rivers, salinity regimes, the estuarine turbidity maximum, and the freshwater–brackish water interface in coastal aquifers. River diversion, channelization, and damming have cascading effects on the TAI continuum by altering sediment transport. If sediment is trapped behind dams, or allowed to flow directly into the ocean bottom, estuarine wetlands at the river mouths may become sediment starved and unable to maintain elevation. Deliberate alteration of hydrology also can be used to create wetlands.

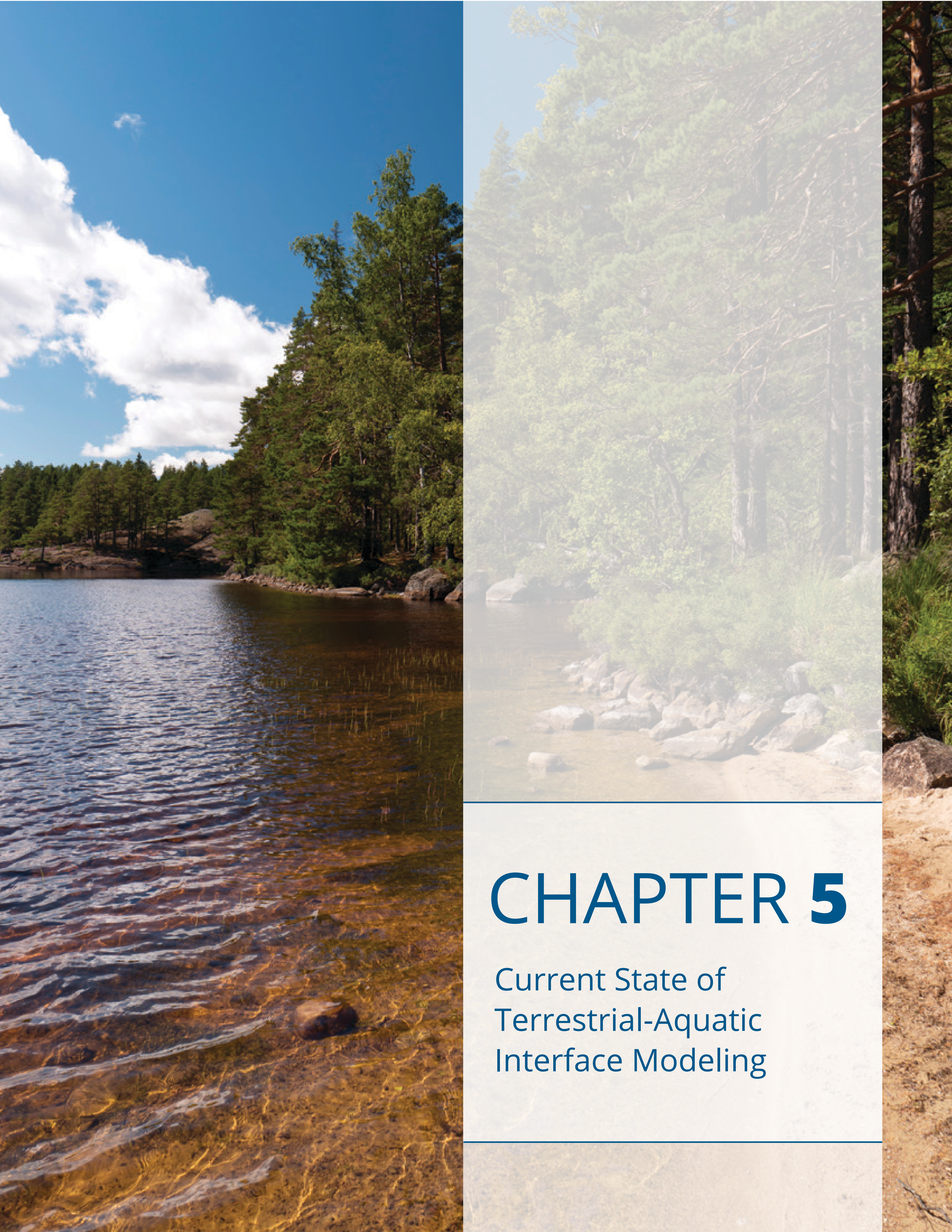
Interactions of climate and human alterations of hydrology are difficult to predict. For example, drought is most commonly associated with reduced annual precipitation, but water-management challenges also can result in lower than desirable water levels with difficult-to-predict climate and environmental patterns. In 2010, El Niño conditions led to water levels that were well above average (Abtew et al. 2011) in the Florida Everglades, followed by higher than average discharges associated with water management. The following year, precipitation amounts lower than average resulted in drought conditions with dry season water depths exceeding the lower tolerance for peat

conservation in Everglades freshwater marshes (Abtew et al. 2012; Sklar et al. 2012). Evident worldwide are climate and environmental impacts on the hydrology of large hydrologic basins, changing total rainfall amounts, extreme rainfall events and evapotranspiration, and interactions with human activities, along with subsequent and altered function of these large basins (Kuhn et al. 2011; Santos et al. 2014). These examples illustrate the sensitivity of TAIs to interactions of climate and hydrology, uncertainties for how they vary by TAI type and setting, the degree of human impact, and feedbacks to environmental management with relevance at large spatial scales.

Disturbance of Organic-Rich Soils

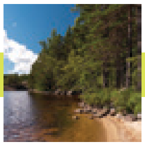
TAI ecosystems such as tidal marshes, mangroves, seagrasses, nontidal floodplain forests, and nontidal peatlands are characteristically rich in soil carbon (i.e., Barr et al. 2010). These large carbon stocks are particularly vulnerable to a variety of disturbances and can emit large amounts of CO_2 and CH_4 to the atmosphere (Pendleton et al. 2012). Climate warming is one driver capable of accelerating carbon loss from the vast stores in wetland soils. Soil carbon pools may be reduced by increased temperatures, changes in local water cycles, nutrient enrichment, changing lability of organic matter inputs, or combinations of these factors. Long-term SOC losses in terrestrial ecosystems with highly organic soils may have significant feedbacks on climate and environmental changes (Lashof and DeAngelo 1997). Comparably, wetlands hold massive stores of carbon that will continue to be susceptible to loss to the atmosphere, also resulting in significant climate feedbacks (e.g., Callaghan et al. 2004). However, recent experimentation with deep soil temperature manipulation has shown no stimulation of carbon loss even to extreme warming in a spruce forest peatland (Wilson et al. 2016). The anoxic and acidic conditions, along with low-quality organic matter in some TAI soils, may limit decomposition rates so severely that warming has no effect. However, this is a preliminary conclusion; warming effects on the stability of soil organic matter stocks remain a major uncertainty in understanding TAI function in changing climates. Models will be useful for determining the extent to which soil warming may be decoupled from air warming in certain systems. For instance, oceanic influences could buffer tidal wetland soil temperatures even as air temperatures rise.

Fire can emit large amounts of greenhouse gases from TAI systems because of their large soil carbon stocks, particularly peatlands and other systems with organic soils (Turetsky et al. 2014). Extensive SOC stocks fuel smoldering ground or subterranean fires that persist for days or weeks after the aboveground fire has passed. Not only does this extended duration of combustion allow for greater soil carbon loss, the combustion products from smoldering TAI fires pose amplified risks for both climate and environmental forcing and human health. Smoke from smoldering fires contain proportionately more pyrogenic carbon than flaming fires, particularly fine particulate matter and black carbon aerosols (Preston and Schmidt 2006). The impacts of TAI fires drew global attention during the severe 1997 and 2015 Indonesian fires, which caused widespread disruption of air travel and produced dangerous air quality conditions for extended durations. SOC stocks can change dramatically after disturbances affect plant primary productivity to reduce carbon inputs to peat-forming soils (Kirwan et al. 2009; Coldren et al. 2016). For example, evidence from several coastal wetland studies shows that highly organic soils can subside or even collapse with saltwater intrusion. The dynamic feedback between plant production and soil microbial respiration that is altered by increasing concentration and duration of salt water and sulfate availability shifts the balance of soil carbon from gain to net loss. This phenomenon, also known as "peat collapse," has been documented to varying degrees across the United States (Cahoon et al. 2003; Nyman et al. 2006; Voss et al. 2013). In coastal wetlands already exposed to disturbances such as saltwater intrusion or hydrologic drawdown, extreme climatic events (i.e., storms and drought) can change the state of TAIs.



CHAPTER 5

Current State of Terrestrial-Aquatic Interface Modeling



5

Current State of Terrestrial-Aquatic Interface Modeling

One of the greatest challenges in effectively modeling terrestrial-aquatic interfaces (TAIs) is that they commonly fall in between traditional domains of existing process-based models. Furthermore, TAIs are isolated within the individual component models of Earth system models (ESMs) so that interactions between systems such as land and ocean or ocean and rivers are poorly captured or entirely absent. Models relevant to TAI processes were developed historically for needs that are (1) too specific to a given terrestrial, wetland, or aquatic system; (2) too coarse in spatial and temporal resolution to capture hot spots and hot moments; or (3) missing fundamental processes important in TAIs. The importance and value of advancing TAI-related science are that this development requires integration and coupling of existing models in new, robust ways. Fortunately, both understanding and modeling of traditional terrestrial and aquatic domains have advanced sufficiently to enable this next phase of model integration. TAIs provide a natural framework for integrating a suite of terrestrial, TAI, and aquatic processes into increasingly sophisticated models across a range of spatial and temporal scales to more robustly capture the occurrence and influence of hot spots and hot moments.

The following sections begin with an overview of ESMs and then discuss the existing state of TAI-relevant models—from high-resolution, process-rich, specialized models to capabilities currently in and being developed in ESMs. In the context of existing capabilities, the sections also highlight critical model deficiencies that must be addressed to overcome the scientific challenges that TAIs present.

Earth System Models

ESMs are intended to represent the global coupled dynamics of mass and energy transfer on model grids (at scales of tens of kilometers), including processes connecting land, atmosphere, ocean, and land and sea ice [see sidebar, Accelerated Climate Modeling for Energy (ACME), and Fig. 15, p. 43]. Current ESMs use land surface representations that explicitly resolve regions on the order of tens to hundreds of kilometers, which enable representations of continental-scale variation connected to features such as major mountain ranges, coastal plains, and river drainages. The most sophisticated ESMs also include statistical representations of finer variations in the land surface, known as subgrid representations. Current multilevel subgrid schemes capture land-surface variations in large categories such as "natural vegetation," "crop," "glacier," "urban," or "lake." Also captured are even finer details within some of these types, for example, the fraction of natural vegetation that each of a number of distinct plant types represents (e.g., trees versus shrubs versus grasses) or the fractional area of wetlands, bare soil, and rock. Processes are represented at multiple spatial scales within ESMs, dictated in part by the governing mechanisms, but also by current knowledge of processes and the ability to generalize process understanding. The model will encompass the enormous global diversity of physical and biological settings. ESMs currently include some simplistic representations of the processes necessary for a predictive understanding of TAIs and the role they play in structuring Earth's climate.

An important limitation of current ESMs with respect to TAIs concerns extreme events, which are poorly

Accelerated Climate Modeling for Energy

The Accelerated Climate Modeling for Energy (ACME) project is central to the U.S. Department of Energy's (DOE) Earth System Modeling program under DOE's Office of Biological and Environmental Research (BER). The Earth System Modeling program supports innovative Earth system model (ESM) capabilities, with the ultimate goal of providing accurate and computationally advanced representations of the fully coupled and integrated Earth system, as needed for energy and related sectoral infrastructure planning.

ESMs couple several component models that represent individual elements of Earth's climate system. Coupled ESM components—such as ACME's Atmosphere, Ocean, Land, Sea Ice, and Land Ice—allow exchange of information such as moisture or heat among components. Launched by BER in 2014, the ACME project simulates the fully coupled Earth system at high resolution, incorporating coupling with energy, water, land-use, and energy-relevant activities.

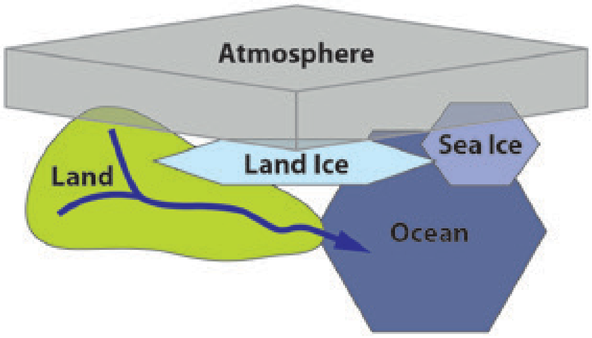
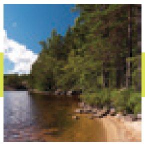


Fig. 15. Accelerated Climate Modeling for Energy (ACME). ACME is an Earth system model supported by the U.S. Department of Energy. [Image courtesy Joel Rowland, Los Alamos National Laboratory]

In Fig. 15, overlapping regions of the ACME model represent model coupling. The Land and Ocean models currently couple in a simple one-way export of river discharge into oceans, or directly to the ocean when land cells do not couple to a river (e.g., from ice sheets in Antarctica and Greenland). Additionally, in regions where a Land model grid cell is closer to the ocean, the model routes a river subsurface flow directly to the ocean. The model also will incorporate the ability to simulate the exchange of water to and from rivers and the surrounding landscape to represent flooding along river corridors. Currently, ACME is in the early stages of developing coastal and estuarine dynamics.

A fundamental attribute of ESMs is the discretization of each model component. ACME is developing atmosphere, ocean, and other Earth system simulation components for use in Ocean, Sea Ice, and Land Ice models in the Model for Prediction Across Scales (MPAS) grid. This hexagonal MPAS grid enables regional variability in cell size to focus higher resolution in areas of particular interest. The Atmosphere and Land models are using a cubed sphere, but ACME is moving its Land model to a watershed-based discretization, as shown in the schematic above.

A major motivation for the ACME project is the paradigm shift to come as computational capabilities move toward the exascale era. DOE, via its science programs, leadership computing centers, and early adoption of new computing architectures, traditionally leads many scientific communities, including Earth system simulation, through ongoing computing changes. The ACME collaborative project spans eight DOE national laboratories, four academic institutions, and one private company. For more information, see the ACME website (climatemodeling.science.energy.gov/projects/accelerated-climate-modeling-energy/).



modeled in ESMs. In part, this lack of representation is due to the short temporal time frames in which TAI processes occur and to ESMs not containing sufficient resolution and detail of forcing features such as mountain ranges and coastal interfaces. While some work has identified where ESMs either perform well or are limited in terms of extremes (Sillmann et al. 2013a, b), this research area is still relatively young. There is a lack of observations of extremes in some cases, particularly for precipitation events and high streamflow that threatens gauge stability. Models with variable resolution capabilities, such as the ACME Land Model (ALM), may be the best means to capture the fine temporal and spatial scales over which extreme events are carried out.

Terrestrial Hydrology and Reactive Transport Models

Just as water is the backbone of TAIs, hydrology models are the backbone of predictive models of TAIs. Capturing the water cycle is the critical first step in predicting any other aspect of TAIs, and nearly every aspect of TAIs is affected by and feeds back on the water cycle. Hydrology models are necessary tools to acquire data validation of processes at work in TAIs and to make predictions about system behavior. A hydrology model can be developed to capture the key hydrological processes that govern flow and transport of water, including dissolved constituents that may affect water quality. With a long history in U.S. Department of Energy applications, hydrology models have an exciting future. Described in this section are the existing and developing classes of hydrology models and the roles they play in TAI research.

Subsurface flow and reactive transport models, originally intended for characterizing waste disposal sites and predicting the fate of contaminants, have long represented subsurface flow through physical solutions of mass conservation. These models use variably saturated formulations to predict soil moisture content as a function of time and space. Driven by this flow solution, the chemical components of primary species are transported and reacted.

In many cases, models exist for individual processes, but gaps exist in the coupling of TAI-critical processes. This is particularly true at scales ranging from soil pores up to soil pedons. Modeling at these scales captures soil characteristics such as surface tension and capillarity that regulate advective and diffusive solute transport. The models must represent grain boundaries and phase interfaces between mobile phases with extremely different viscosities and densities. Codes implementing the models must address these unique, process-driven challenges while simultaneously being computationally efficient and scalable enough to solve these problems on domains large enough to represent a continuum of grains. Although progress on these challenges has been made in the fields of secondary oil recovery and contaminant transport (Hassanizadeh and Gray 1993; Lichtner and Kang 2007), there is a need for fundamental research before such models are able to capture small-scale TAI phenomena that have large-scale implications.

Simultaneously, hydrology-specific models designed for the characterization and prediction of a watershed have been developed. Typically, hydrology models divide the watershed into (1) the land base on which precipitation falls, interacts with vegetation, and moves through or on soils and (2) the riverine environment, which governs the movement of water and nutrients down the channel and eventually into lakes or estuarine environments. Land models generally are classed into "lumped" or "distributed," and "deterministic" (process based) versus "stochastic." The most relevant for understanding TAIs are distributed, process-based models (Condon and Maxwell 2015; Painter et al. 2016; Shen et al. 2016). These models use various formulations of subsurface and surface flow, along with many other sources and sinks of water (e.g., evaporation and transpiration) to determine the water balance for a particular land unit. They must include accurate descriptions of the watershed if they are to adequately perform and provide useful information such as on

rate, volume, and timing of flow and also include vegetation, soils, and topographic information (e.g., elevation, aspect, and slope).

At the ESM scale, the limited roles played by lateral flow and computational speed and capacity motivate a class of coarse-resolution models (i.e., at scales of one to hundreds of kilometers) based on columns. Vertical infiltration is solved on each subwatershed land surface, and lateral flow is characterized through overland routing models and base flow models. This runoff and base flow is then collected and passed to a riverine model (Clark et al. 2015). Given accurate inputs of surface weather over land (e.g., precipitation, temperature, humidity, incoming radiation, and winds), current global-scale and large-scale models can capture many of the large-scale features of observed water flow from major rivers into oceans, including the quantity and seasonal and interannual variations in flow timing (Zaitchik et al. 2010).

Current river routing models focus on the transport of liquid water (including, in some cases, ice). In development are explicit energy balance models that will allow prediction of stream temperatures across a range of scales from headwater streams to major rivers and over the full range of climate and environmental forcings from tropical rivers to ice sheet drainages (Li et al. 2015). These same modeling platforms also are being extended to include biogeochemical processes that influence the transformation of organic matter as it moves from headwater streams through river channels and into estuaries. Energy and biogeochemistry components of river models also are being integrated with simulations of new physical processes that allow two-way interactions between land and stream via processes such as inundation (Clark et al. 2015). On the TAI land side, new aspects of the subgrid representation being introduced enable models to resolve the influences of varying elevations, terrain slopes, and aspects (e.g., compass orientation). Finally, the best current land models within ESMs also include significant resolution of vertical connections (Tang et al. 2013; Tang and Riley 2016), called column dynamics, within the soil. Vertical transports of energy, water, and organic matter are represented in layers extending many meters below the surface. This existing capability can facilitate simulation of groundwater interactions and connections between land and aquatic systems through the hyporheic zone.

Recent and ongoing efforts, enabled by increasing computational resources, are investigating a set of process-resolving, hyper-resolution models (HRMs; at scales of 10 meters to 1 kilometer) with three-dimensional (3D) flow. These models solve Richards' equation in 3D, coupled through pressure and flux continuity to approximations of the shallow water equations for surface flow. Given the vast availability of these codes, there have been several extensive Model Intercomparison Project (MIP) efforts, which elucidate the differences and similarities on both simple and more realistic simulations (Grenier et al. 2015; Kollet et al. 2017; Maxwell et al. 2014).

To capture water sources and sinks such as precipitation, evaporation, and transpiration, these models employ a wide variety of complexities—from parameterizations to coupling existing column representations of vegetation and biogeochemistry and from global models to coupling process-resolving, scale-appropriate models of vegetation. While the core of these models is hydrology, they also can have complex representations of canopy, litter and duff layers, root water uptake and plant hydraulics, and vegetation dynamics, and they could be coupled to state-of-the-art dynamic vegetation and biogeochemical models.

As HRMs become more mature, these model types promise to become subgrid components within coarse-resolution ESMs (i.e., upscaling) and to determine to what degree HRMs influence climate and environmental characterizations at regional and local scales (i.e., downscaling). At the global scale, ESMs do not yet incorporate the hydrologic process understanding that is well represented in HRMs, especially that of surface-groundwater interactions and extreme events. With the necessary finer-scale representations of many climate and environmental characteristics—particularly in terms of water availability, timing, and quality as well as their resulting effects on human and engineered systems—these HRMs have much to offer. Their successful inclusion will require exascale computing resources and strategies such as asynchronous multitask parallelism. The localized nature of these subgrid models make them well suited to extreme parallelism, but significant work remains.

Terrestrial Ecosystem Models

The wide variety of ecosystem-scale models can be broadly categorized as population models, demographic or distribution models, and individual-based models (Porté and Bartelink 2002). Such models range in spatial scale levels from plant to stand to landscape. Although superficially seeming to represent a broad range of diversity, most of these models tend to rely on very similar underlying principles and assumptions (Hawkes 2000). Specifically, they tend to share many characteristics in their modeling of the abiotic and biotic system state, with discrete compartments tracking carbon and other elements, fixed time steps, and first-order soil carbon kinetics, and with a focus on aboveground plant production and biomass (for a counter example, see Grant 2015). Such models also have traditionally focused on forested ecosystems, a consequence of their origins as forestry yield tables (Pretzsch 1999) that were designed to assess the importance of forests in the global economy, climate, and carbon cycle (e.g., Hanewinkel et al. 2013).

Applying such models to mineral soil wetlands, peatlands, and other terrestrial-aquatic systems is problematic because these ecosystems have characteristics that are dominant in upland systems. These traits include high and fluctuating water tables, high-clay or organic soils (i.e., Histosols), significant methane (CH_4) production and consumption, anoxic soil and low soil reduction-oxidation (redox) potentials, and the presence of productive bryophyte communities. These characteristics are all poorly treated by most upland models (Trettin et al. 2001). Indeed, terrestrial model-data synthesis and comparison studies exhibit varied performances when run under fluctuating soil moisture conditions characteristic of wetlands and other TAI systems (Sulman et al. 2012; Zaehle et al. 2014; Keenan et al. 2012).

Efforts have been made to incorporate TAI-relevant processes into some upland models. For example, the addition of depth-explicit soil moisture, water storage, and nonvascular vegetation (i.e., bryophytes) to the Biome-BioGeochemical Cycles (BGC) model (Engstrom and Hope 2011; Bond-Lamberty et al. 2007) or Photosynthetic/EvapoTransiration (PnET) model (Zhang et al. 2002), or fully prognostic water table calculations to the Community Land Model (CLM; Shi et al. 2015). These additions have improved the ability of models to accurately simulate TAI dynamics, but much remains to be done because effective simulation of such systems requires modeling anaerobic pathways; organic soil layers and peat deposits; vertical and horizontal water flow; and solute transport, soil oxygenation, and redox potential (Baird et al. 2009).

Dedicated wetland models incorporate many of the hydrological and biogeochemical complexities characteristic of TAIs. They can incorporate characteristics that are difficult to capture using traditional upland models, such as anaerobic biogeochemistry, deep organic-rich soils, dynamic soil surfaces that change elevation, shallow water tables, and plant species with novel morphology and ecophysiology (e.g., bryophytes). Because wetlands store massive quantities of carbon and exchange both carbon dioxide (CO_2) and CH_4 with the atmosphere, these ecosystems play an important role in the global carbon balance and potentially could accelerate global warming (Ringeval et al. 2011). Several recent regional and global wetland model-data comparison studies concluded that important sources of uncertainty in model predictions of CO_2 and CH_4 emissions included (1) the seasonal effects of inundation on the position of the terrestrial-wetland interface, (2) representation of inundated plant processes such as gas transport through aerenchyma, and (3) wetland subsurface biogeochemistry

(Bohn et al. 2015; Melton et al. 2013). The current ALM (version 1) has a representation of these processes (Riley et al. 2011), as do other ESMs, but much work remains to ensure these models accurately predict greenhouse gas emissions under a changing climate (for a review, see Xu et al. 2016b). Missing components are, for example, tolerance for varying salinity conditions, interactions with anoxic environments typical in the shallow subsurface of many wetlands, and response to periodic inundation. A critical limitation of ESMs, and ecosystem models in general, arises because they typically conceptualize the landscape as individual, autonomous grid cells that exchange carbon and energy fluxes with the atmosphere but lack any cell-to-cell interaction or transport (McGuire et al. 2001). This simplification becomes untenable when modeling TAIs and highlights the need to couple these models with hydrology models capable of accurately predicting hydrologic fluxes across the landscape.

Estuarine Models

Rivers draining into coasts transition from freshwater systems with unidirectional flow to tidal freshwater rivers, to tidal saline rivers and estuaries that vary from oligohaline to fully saline. Although river estuaries form a natural TAI continuum, communities of scientists have traditionally isolated their research to either tidal or non-tidal portions of the continuum, and estuarine scientists have focused on saline reaches. Because tidal freshwater ecosystems are neither free flowing nor saline, there is a particular absence of research in these common TAIs. As a result, there is an urgent need to integrate terrestrial and riverine models with estuarine models.

Estuarine models are formulated to physically diagnose the hydrodynamics and transport resulting from stratified flows that arise from the exchange and interaction between saline ocean water and fresh riverine water. These models are designed to operate in the intertidal environment where periodic wetting and drying of nearshore tidal flats and marshlands are common. Example applications of estuarine modeling revolve around questions of tidal circulation and flushing, coastline evolution (e.g., via sediment transport), ecosystem function (e.g., wetland restoration), and water quality modeling (e.g., the location of salinity, turbidity, or phytoplankton bloom fronts with respect to water intakes). Some estuarine models include biogeochemical modules that simulate submerged aquatic vegetation, marshes, and sediment diagenesis, but these formulations are primitive and ignore processes such as export of solutes from soil porewater and ecosystem feedback capable of dynamically changing soil elevation.

The hydrodynamics in these models typically solves a simplified set based on the Reynolds-averaged Navier-Stokes (RANS) equation, which assumes flow is due primarily to tidal and meteorological forcing. Components involving assumptions of hydrostatic pressure and decoupling of horizontal and vertical turbulences ensure a vertical log-law profile and stability under horizontal shears (e.g., at a river confluence). Advanced models employ 3D RANS turbulence modeling and nonhydrostatic pressure. Ultimately, the fundamental challenge in estuarine modeling is obtaining the correct datasets in bathymetry, shoreline geometry, forcing, biology, and validation, which often are sparse and incomplete. Forcing is particularly important in these systems because wind, waves, tides, and seasonal and episodic heating of the water can drive strong flows that occur in complicated geometries including bays, tidal river networks, and deltas. Input data required to build and validate an estuarine model include wind, waves, tides, turbulence, sediment transport, biogeochemistry, climatological data (e.g., solar forcing), bathymetry, and *in situ* observations via Acoustic Doppler Current Profilers, thermistor chains, and Lagrangian drifters. Typically, modeling occurs at 1 to 100 meters in spatial resolutions and temporal resolutions on the order of seconds; it is, therefore, unable to directly simulate turbulence, although modeling at finer scales is becoming more common.

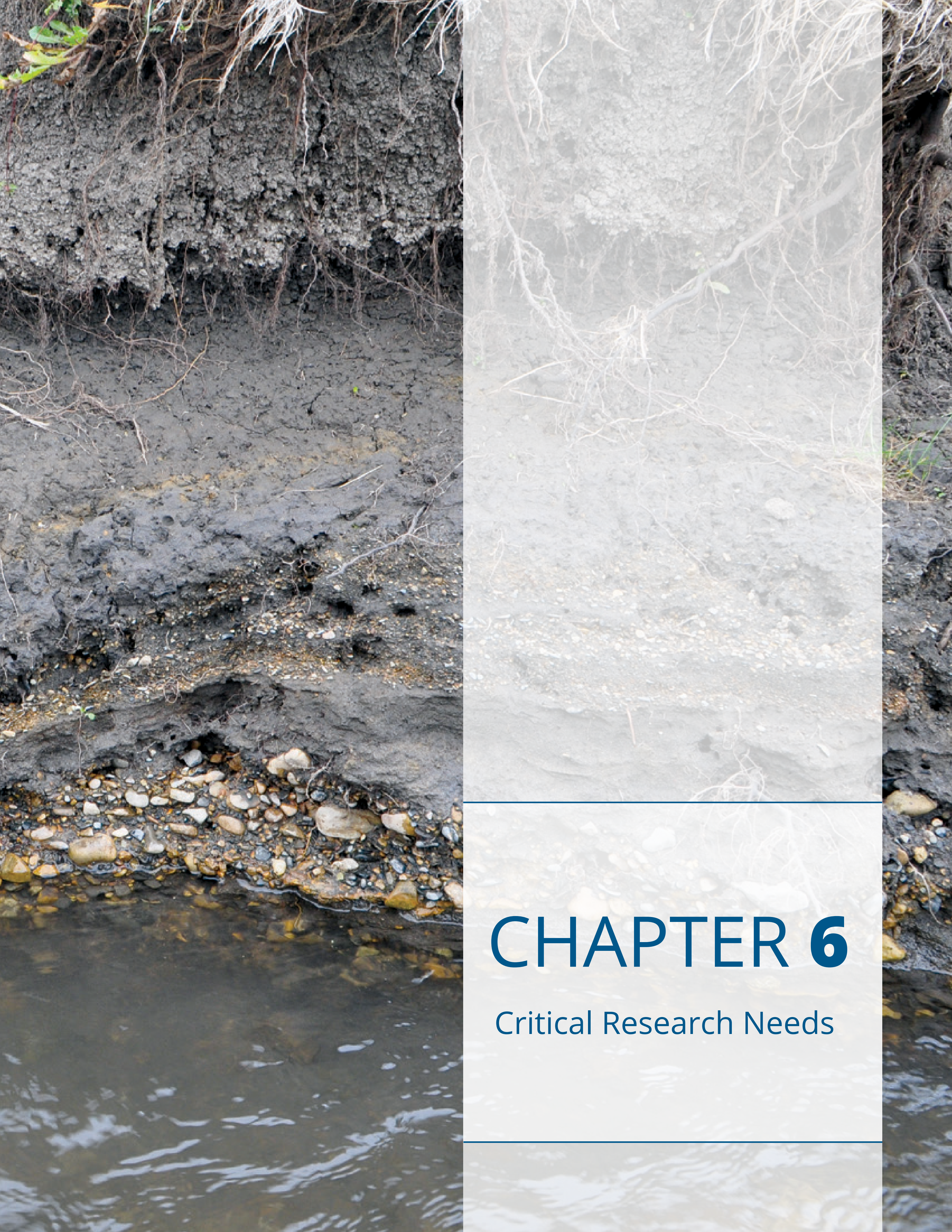
There are two general classes of estuarine models: structured and unstructured grid models. Unstructured grid models have gained popularity in the last decade, exhibiting the ability to represent complex estuarine geometry better than traditional structured grid approaches. Premier unstructured grid models incorporate key processes that are needed to simulate fully coupled estuarine systems arising from flow, sediment, and ecological interactions. Models will vary in their numerics, but the state of the art typically includes generalized discretizations, especially in the vertical coordinate. Knowledge and varied applications of different numerical techniques that are appropriate to different physical geometries and forcing have evolved from multidecadal modeling efforts to diagnose and apply best-practice numerics for estuarine modeling. Unlike the industry-standard Delft suite of models, unstructured research codes typically can be run in a high-performance computing context and are scalable to hundreds of processors.

Despite existing capabilities, this community lacks a MIP for evaluating different modeling systems inhibiting adoption of a single model for use in arbitrary applications. To fully integrate land, river, and ocean modeling, these models should be able to seamlessly transition from 1D to 3D modeling, so that modeling of upstream rivers remains computationally inexpensive while still capable of resolving complex 3D flows within estuarine bays. This capability requires computation of 3D turbulence modeling and nonhydrostatic pressure.

Current ESMs do not capture estuarine processes or dynamics. These models represent the distribution of freshwater fluxes into ocean cells near river outlets. As river biogeochemistry advances, these flux components will become more sophisticated and enable simulations of estuarine biogeochemistry. Recently, box models have been tested as a computationally efficient way to represent the influence of estuaries on the mixing and distribution of estuarine waters and chemistry with the open ocean (Tseng et al. 2016). The ability to locally increase spatial resolution in the ACME Model for Prediction Across Scales-Ocean (MPAS-O) provides the potential to explicitly represent estuaries, although additional hydrodynamics will be needed to capture the influence of waves, tides, storm surges, and rising sea levels. Linking the ocean to the land in a way that enables the exchange of sediment and a changing coastline is an even greater challenge for accurate representation of coastal TAIs in ESMs.

Coastal Ecosystem Models

The stability and resilience of coastal ecosystems depend on the loss and gain of land related to rates of sea level rise and inundation. As discussed previously, this balance of land critically depends on the health and growth rate of vegetation within these ecosystems (see Fig. 10, p. 25). Recent efforts to quantify the trajectory of coastal ecosystems under land-use, climate, and environmental changes have sought to couple physical and biological (ecogeomorphic) processes in numerical models (Kakeh et al. 2016; Kirwan and Mudd 2012; Mudd et al. 2009; Swanson et al. 2014). These models incorporate above- and belowground plant growth, along with erosion and deposition of sediment in one dimension, to predict the gain and loss of land under a range of forcings and based on empirical data for plant dynamics for a variety of coastal species. Although these models represent an important advancement in understanding and predicting the fate of coastal ecosystems, to date, this level of complexity in ecogeomorphic process feedbacks has yet to be incorporated into or coupled with physics-based models of estuarine dynamics and morphodynamics models that are used to predict the physical evolution of coastal settings via the use of hydrodynamics and sediment-transport equations. Incorporation of these models into ESMs will require advances in both ecogeomorphology and coastal ocean modeling as well as robust model coupling that enables dynamic interactions between land and ocean.



CHAPTER 6

Critical Research Needs

6
Critical Research Needs

Integration of Measurements, Modeling, and Experimentation

Generally, research approaches to investigating terrestrial-aquatic interface (TAI) ecosystems must lead to new understanding about the role of these transitional ecosystems at the juncture of land and water in the Earth system, as well as the impacts of climate on the sensitive interfaces of terrestrial and aquatic environments and ecosystems. Neither the three-dimensional (3D) spatial structures of these TAI ecosystems, nor the biophysical transfers and feedbacks of matter and energy throughout their structures, are currently well understood or modeled. Moreover, the net effect of transport processes through these ecosystems transforms their spatial structures, producing highly dynamic geomorphology and plant community structures. These dynamic structures, in turn, control aspects of element and water cycles. Thus, achieving fundamental new understanding about the role of TAI ecosystems on a global scale will require a research program that integrates mapping, measurement, and modeling. This chapter discusses these three approaches in more detail.

An observer of Earth's terrestrial biomes naturally would conclude that TAI ecosystems are biologically diverse, just from recognizing the visible evidence of differences among temperate, tropical, and boreal forests, grasslands, and deserts. All biomes contain both terrestrial and aquatic ecosystems. Quantifying differences between them and identifying which have the most influence on element and water cycles are key challenges for a TAI research program to improve Earth system modeling. Whereas some of these ecosystems may be large and relatively homogenous in function, and thus more easily characterized, others may be smaller and more heterogeneous yet still have large impacts. Prioritizing research accordingly to account for spatial heterogeneity in the area, volume, and elevation of wetlands at regional and global scales will help to save resources.

Careful integration of modeling with the collection of observational and experimental data will in large part determine the research program's success. Given the likely importance of extreme events to these ecosystems, an understanding of such events and their effects is necessary to determine which are most characteristic of each biome. Similarly, knowledge of the most important drivers of key biophysical processes, such as reduction-oxidation geochemistry, is foundational to effective predictive modeling, as is an understanding of the scaling properties of biogeochemistry and transferability among scales. Both extreme events and environmental drivers are also components of the risks and thresholds of ecosystem collapse related to the effects of climate and environmental changes.

The horizontal and vertical extent of TAI ecosystems has not been measured and thus is currently unknown, in part because of definitional challenges. Overcoming this issue is not a simple mapping problem. The inherent hydrodynamics and morphodynamics, which are essential elements of these systems, make developing standard practices necessary for measuring boundaries. These boundaries must incorporate disturbance regime factors such as the frequency, duration, and magnitude of inundation and their consequences for geomorphic structure within process domains. Thus,

boundaries are not always visually discernible and are identifiable even less frequently through conventional remote-sensing techniques. A salient example of the challenges inherent in this type of mapping is floodplain forested wetlands, whose canopies resist penetration by remotely operated sensors and contribute to the wetlands being easily confused with nonwetlands when there is no topographic and hydrologic data for modeling. The relevant methods for a 3D characterization will include integrated remote sensing, topographic mapping, and hydrologic modeling with change analysis of geomorphological features within process domains.

A key focus will be on measuring the fluxes, temporary storage, and transformation of particulate and dissolved matter (e.g., organic and dissolved organic carbon) through TAIs such as riparian areas of headwater streams, river floodplains, and the littoral or intertidal zone along coasts. These efforts should include (1) measurements of partial pressure carbon dioxide (CO_2) and oxygen fluxes, which are surprisingly sparse in the literature; (2) tracer studies of lateral and vertical transport to define the boundaries of process effects (e.g., Mulholland et al. 2008); (3) mesocosm studies (e.g., Jonsson et al. 2014); (4) biophysical-scale models; and (5) experimental manipulations to elucidate the drivers of key ecosystem processes. Recognizing the need for plant and microbial studies is essential to assessing the factors that regulate biogeochemical transformations in TAIs. These factors include allocation to roots and shoots by plants, biophysical transport of gases to root and stem tissues, and tissue nutrient concentrations. In some cases, such as tissue nutrient concentrations, measuring these features through remote sensing can support extrapolation to the global scale (e.g., Arrigo 2004; Malenovský et al. 2009).

Improving the understanding of TAI responses to extreme events is crucial to advancing knowledge of both the scale (temporal and spatial) of disturbances and the resulting interplay of their ecological and environmental feedbacks that interact at the scales of extreme-event phenomena. Field observations and controlled experiments are important means to gather this information for inclusion in models. Also bolstering model-validation efforts will be improved observations of extreme precipitation, temperature that leads to changing patterns of runoff, and soil moisture and snowpack. Through improved understanding and representation of these events in models, scientists can examine the impacts of extremes on TAIs, such as drought and low flows. Without this information, knowledge of system stability and important interactions that may sustain or subdue TAI responses is incomplete and unclear.

The selection of study sites must meet multiple requirements and be conducted following the mining of open data available for TAI ecosystems both within and outside the United States. Workshop participants agreed on the need to address the primary research questions through a balance between long-term observations using sensors dispersed at broad spatial scales and “extensive” and “intensive” measurements of watersheds and smaller sites.

Multiscale Models

A wide variety of ideas have been used and others proposed for advancing process understanding across scales, both up and down. Frequently, these ideas come to a choice between “embedding models” versus “embedding understanding”; both approaches can be appropriate for different systems. Embedded understanding gives a name to a regularly used scientific approach—that is, simplifying physics while trying to maintain the essence of the details—a key strategy for all models. This process can be as simple as selecting effective parameters that average over subgrid heterogeneity or, more effectively, developing empirical, subgrid models that capture the predictions of fine-scale, process-resolving models in a simplified form. Alternatively, users of embedded models strive to build fine-scale, process-resolving models directly, often in a stochastic or localized way. The technical and theoretical challenges of this strategy can be quite difficult, and both can cause derailment. Technical challenges include information passing and multilanguage compilation, and theoretical challenges include ensuring that the information passed between scales is both appropriate and relevant. However, when chosen with care, both strategies can be extremely effective at capturing the essence of finer-scale processes in a coarser-scale model. These choices combine scientific intuition with formal mathematical methods; the resulting multiscale model must be evaluated carefully against observations at multiple scales.

Examples of embedding understanding are subgrid parameterizations, which are used extensively in global land models and intended to represent a spatially heterogeneous or complex process in an averaged or simplified model. Examples of these subgrid parameters include water-retention models in hydrology, big-leaf vegetation models, and biogeochemical models. All have the advantage of being reasonably well understood, and many codes naturally enable the inclusion of new and improved parameterizations, making them easy to couple into existing coarser-scale models. However, frequently in coupled systems, simple subgrid parameterizations do not sufficiently represent the underlying physics, chemistry, or biology to address issues involving process interactions. In such cases, embedded models are necessary, and describing uncertainty is imperative, based on assumptions invoked with the parameterizations. This requirement implies that creative and new approaches are desired (e.g., those that explore the application of scale-aware parameterizations, mesh-to-mesh interpolation, code-to-code data passing, and efficient use of computational assets).

Alternatively, reduced-order models (ROMs) aim to run process-resolving models under a variety of conditions and then develop emulators or surfaces that fit model output as a function of a few key indicator variables. ROMs represent a promising strategy for simplifying the computational needs of subgrid, embedded models. However, these ROMs cannot be used in conditions outside the original training datasets. New research in dynamic ROMs and emulators that can be continuously updated as the system changes between states and into no-analogue futures might remove some of these caveats.

The ongoing development of process-resolving models creates valuable research opportunities for multiscale Earth system models (ESMs). Most ESMs currently include some scale hierarchy that allows representation of multiple land types in a single grid cell. This arrangement provides the opportunity to insert subgrid models, potentially in a spatially and temporally dynamic way, helping to address TAI characteristics as hot spots and hot moments. As episodic or extreme events occur, subgrid simulations of a process-resolving model can be spawned in an adaptive way. This strategy may be particularly relevant to TAIs, which fundamentally are below the resolution of a single ESM grid cell. Furthermore, embedding ensembles of runs within such a framework would provide the needed uncertainty estimates to inform impact assessments. These strategies necessarily would leverage exascale computing because their computational cost, while extremely expensive, would be highly parallelizable.

Because TAIs are characterized by their tight coupling of hydrology, geomorphology, ecology, and biogeochemistry, modeling of these zones requires tackling a diverse landscape of existing legacy codes, new model and model-coupling developments, and uncertainty in process physics. There is significant uncertainty in the structure of TAI models, not just in their parameters; thus, new efforts should be cognizant of this significant software challenge. Coupling state-of-the-art models across disciplines for TAIs demonstrates the need for a virtual ecosystem of software, with well-defined interfaces, built on advancing research in software frameworks for model structure exploration (e.g., Coon et al. 2016). In these cases, the metric for an efficient code often is measured in developer time, not model run time. The development of new TAI models should leverage and extend new and emerging technologies in interface design and functional multiphysics frameworks. These technologies should spur quick development and testing of new models and their coupling to existing models along with evaluation

against data and observations. Furthermore, these models and coupling must use modern software development best practices to ensure correctness and model accuracy despite the extreme complexity inherent in tightly coupled systems.

Multiscale Experiments and Their Integration with Predictive Models

A major challenge is understanding how perturbations cascade up and down spatiotemporal scales to affect key TAI ecosystem functions. Gaining that mechanistic understanding outside observable system drivers and states requires going beyond single-scale observations in natural settings via multiscale experimental manipulations. Multiscale experiments provide unique understanding on how processes play out across scales in these ecosystems. One reason is that the effect of a given perturbation likely depends on the scale of the system it is perturbing.

Although a broad range of studies likely could be conceptualized as a multiscale experiment, in this case the focus is on three classes of experiments that are not mutually exclusive. They include (1) direct manipulation of a system's spatial scale, (2) manipulation of a larger-scale driver followed by tracking the responses of smaller-scale features, and (3) distributed networks of single-scale manipulations to link smaller-scale perturbations to larger-scale phenomena.

Direct Manipulation of Scale

One class of multiscale experiments invokes treatments that include direct manipulation of the spatial scale of the system being observed. This type of experiment might evaluate how the scale of an experimental system alters system function or response to perturbation. For example, Petersen et al. (2003) summarized coastal-zone experiments that manipulated the spatial scale of open water mesocosms. From these experiments, scaling relationships for primary production and zooplankton biomass were developed that applied to a larger-scale natural system (Chesapeake Bay). Importantly, Petersen et al. (2003) found that experimentally derived scaling relationships did not apply for nitrogen recycling.

This finding highlights a key TAI knowledge gap—understanding which phenomena can and cannot be scaled or predicted from multiscale experiments. Phenomena that cannot be directly up-scaled will require particular attention in terms of understanding critical control-point mechanisms, including those that lead to scale transitions that occur at scales beyond those involved in manipulative experiments.

Knowledge of which features and processes can be represented as directly up-scaled parameters, and which cannot, is essential for efficiently coupling empirical data from multiscale experiments to predictive multiscale models. In the earlier example, empirically derived scaling relationships for primary production and zooplankton biomass could be used to efficiently up-scale the small-scale observations as parameters for use in larger-scale simulations. In contrast, up-scaling the nitrogen recycling rate from small-scale experiments may require highly resolved (and computationally demanding) process models. Understanding when parameters can be empirically up-scaled versus when process models are required is a major challenge in TAI ecosystems due to their inherent multiscale organization.

Manipulation of Large-Scale Drivers

Another class of multiscale experiments manipulates a larger-scale (e.g., landscape-scale) driver and studies the responses of smaller-scale system features and functions. This type of experiment also might make observations—in response to experimental perturbations—across a range of spatial and temporal scales. For example, Lan et al. (2015) experimentally evaluated the scale dependence of nitrogen-deposition impacts on plant species richness within a grassland system. The scientists defined a key nitrogen threshold in the system (referred to as N_{crit}), which is the amount of nitrogen enrichment above which there is a significant decline in species richness (the number of species per area). Lan et al. (2015) found that this threshold increased strongly with spatial scale. Thus, more nitrogen can be deposited in larger-scale systems before there is significant loss of species richness.

The Lan et al. (2015) study could be directly translated to TAI ecosystems to examine how scale modulates the nitrogen-deposition impacts (or other system-relevant perturbations) on biological diversity. A useful approach for such studies also would be to take a multitaxon or multimetric approach to examine shifts in species richness and functional trait diversity within plants, animals, and microorganisms that result from their combined influences over the functioning of TAI ecosystems.

Experiments that examine the scale dependence of drivers such as nitrogen deposition do not necessarily reveal underlying processes, but they do provide powerful constraints on multiscale models. That is, observed scale dependencies should be predictable from a multiscale model that faithfully represents key processes (see sidebar, Spruce and Peatland Responses Under Climatic and Environmental Change, and Fig. 16, p. 55). An inability to predict such scale transitions may indicate structural deficiencies. In this case, additional experiment-model iterations would be needed to elucidate processes that cause observed scale dependencies. Such an approach, which ultimately will lead to improved process representation, is critical for robust predictions in TAI ecosystems because of the ongoing environmental changes that are pushing these systems beyond the environmental conditions used for model calibration.

Distributed Networks of Single-Scale Experiments

Distributed networks of single-scale experimental manipulations can be conceptualized as a multiscale experiment that is used to understand how smaller-scale perturbations scale up to influence larger-scale phenomena. This type of experiment imposes a consistent set of perturbations and makes a consistent set of observations across a broad range of systems (e.g., across biomes). This design is multiscale in the sense that results can be aggregated at different spatial scales or across different environmental extents to examine the context dependence (and scale dependence) of perturbation impacts.

There are good examples of spatially distributed observation networks [e.g., the National Ecological Observatory Network (NEON) and AmeriFlux Network], but relatively few are broadly distributed manipulative experiments. One exciting exception is the Nutrient Network (NutNet), which has established equivalent nutrient-addition experiments in grassland ecosystems around the world. This approach has generated novel insights that could not be achieved using single-site experiments. For example, Stevens et al. (2015) showed that nitrogen deposition consistently increased annual net primary production in grassland systems, regardless of climate or other local conditions. This finding suggests that nitrogen deposition impacts on grasslands lack historical contingencies. On the other hand, O'Halloran et al. (2013) used NutNet data to reveal context dependencies in the relationship between primary production and decomposition rates.

Although distributed networks have been used in both terrestrial and aquatic ecosystems (Fraser et al. 2013), there is a need for distributed experiments to TAI ecosystems because of their very broad ranges of associated environmental conditions (e.g., coastal to freshwater and rainforests to deserts). For example, a network of sites that consistently imposes different levels of salt water intrusion on tidal freshwater systems would significantly contribute to and advance the understanding of how sea level rise will impact these critical TAI ecosystems. Because such an approach combines controlled manipulations with cross-system observations, experimental outcomes can (1) provide empirical constraints—likely varying across systems—against which to calibrate and evaluate models and (2) reveal mechanisms that underlie observed context dependencies and, in turn, improve process representation in predictive models.

Spruce and Peatland Responses Under Climatic and Environmental Change

Terrestrial-aquatic interface (TAI) ecosystems such as peatlands, tidal marshes, mangroves, and non-tidal wetlands accumulate large soil carbon pools. These carbon stocks may be vulnerable to accelerated decomposition when disturbed by drainage, erosion, and climate change. Peatlands cover only 3% of Earth's land surface but contain about 30% of the global soil carbon pool. The Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) project is an experiment that simulates the response of northern peatland ecosystems to higher atmospheric carbon dioxide (CO_2) concentrations and temperature. Led by Oak Ridge National Laboratory, the SPRUCE experiment is assessing a decade of responses to these perturbations across multiple scales of ecological organization, including microbial communities, moss populations, vascular plant species, and some insect groups. To identify and quantify these critical environmental response mechanisms, the Terrestrial Ecosystem Science program within the U.S. Department of Energy's (DOE) Office of Biological and Environmental Research supports this whole-ecosystem experiment in northern Minnesota (see Fig. 16). SPRUCE provides a platform for testing mechanisms controlling the vulnerability of organisms, biogeochemical processes, and ecosystem functions to important environmental change variables. Examples are thresholds across which populations increase or decline, limitations to regeneration, biogeochemical limitations to productivity, and the cycling and release of CO_2 and methane.

Fig. 16. Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) Project Site. Interior of a SPRUCE open-topped warming enclosure showing natural snow accumulation during a mid-winter precipitation event in Minnesota. [Image courtesy Oak Ridge National Laboratory]

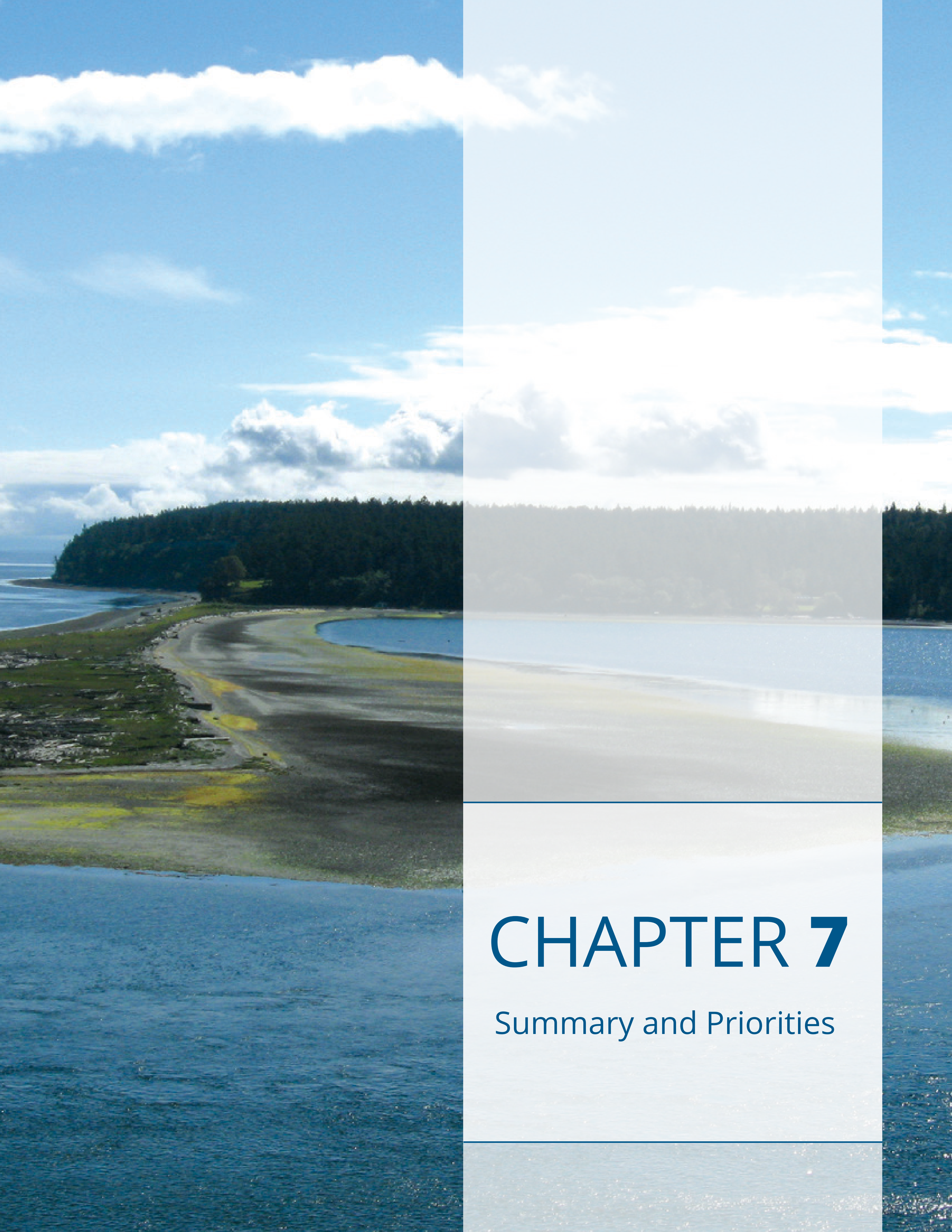
The SPRUCE project connects observations to new modeling approaches for improved climate predictions, incorporating the complex relationships among warming, drying, microbial processes, and vegetation responses associated with climatic change. This comprehensive suite of spruce-dominated peatland process studies and observations accelerates model development by improving the representation of processes, model calibration, and model validation for boreal systems. Insights come from both small-scale processes and landscape-relevant water, carbon, and energy fluxes for similar peatlands. SPRUCE is a cooperative joint venture by scientists from DOE national laboratories, the U.S. Department of Agriculture's Forest Service, and universities. For more information, see the SPRUCE website (mnspruce.ornl.gov).

Watershed Approaches

Quantification and predictive modeling of coupled hydrological and biological processes within interconnected hydrological systems necessitate a distributed network of observational sites spanning a diversity of ecosystems in multiple regions, climates, and land uses. While such a network of sites already exists within federally supported programs, these sites are focused only marginally on assessing process-level connectivity among ecosystems, often treating each as a unique feature of the landscape. Surprisingly lacking are studies seeking to bridge multiple sites spanning a broad continuum from headwaters to coastlines via an interconnected observational and modeling framework. In contrast, a coordinated research program designed to integrate research activities and assimilate observational, experimental, and modeling efforts across the current constellation of field study sites within the United States is warranted both to enhance multiagency collaborative efforts and to advance the state of the science. Examples include the U.S. Department of Energy's (DOE) Next-Generation Ecosystem Experiments and Scientific Focus Area field sites, the National Science Foundation's Critical Zone Observatories and NEON, and the National Oceanic and Atmospheric Administration's National Estuarine Research Reserve System. Research activities within DOE's Climate and Environmental Sciences Division in the Office of Biological and Environmental Research have emphasized data-model integration as a guiding principle for quantifying and predicting ecosystem behavior and its response to episodic and multidecadal climate drivers leading to extreme events. Moreover, numerous DOE field studies supplement purely observational data with those derived from experimental manipulation of key environmental states, such as temperature and soil moisture, to resolve mechanistic- and process-level behavior. These data can be embedded within ESMs, which are used subsequently to identify gaps in process understanding and to guide future experimental activities (Covino 2016).

To elucidate the role that TAIs play in regulating the flow of water and nutrients within interconnected hydrological systems along the "summit-to-seas" continuum, the critical research need posited for achieving this goal is to develop an interconnected, coordinated network of field observatories. Placing a network of observatories within a unifying modeling context is well aligned with existing DOE research activities in both the Terrestrial Ecosystem Science and Subsurface Biogeochemical Research programs. Recognizing that key ecosystems may be underrepresented within the existing national network of observatories (e.g., coastal zone environments), these programs may require additional resources to expand and develop observational capabilities in such areas. The use of a unifying ESM (or models) enables bridging of scales and study sites in a manner that largely obviates the need for a continuous chain of sites along a single interconnected hydrological system. Data-model integration activities are coordinated and expected to identify key system components and compartments within the network, along with key environmental parameters that must be measured in a consistent manner from site to site to constrain and calibrate models and validate their predictions.

Given the diversity of TAI systems identified in this workshop report that exert critical controls on water and nutrient export, only a broad network of field study sites appears capable of capturing the level of process information needed to populate predictive models describing their behavior. Building on and expanding where needed the existing distributed network of field observatories and assimilating the key data types derived from each of them into predictive models describing TAI processes represent the most feasible means to make rapid progress in this research area. Additionally, the legacy of preexisting data made available through direct engagement of the network of observatories is expected to greatly expedite the process of data assimilation within predictive models describing TAI phenomena. Focusing on a single site or sites that fail to account for the diversity of systems identified in this report would limit broad research relevance and applicability across scales important to quantifying the role of such systems in regulating continental- to global-scale water, carbon, and nutrient budgets.



CHAPTER 7

Summary and Priorities

7
Summary and Priorities

The critical terrestrial-aquatic interface (TAI) is not characterized by geographic location; it is defined by physical interactions that drive keystone processes. In contrast to recent perception, this interface is not merely a conduit through which soluble and particulate materials are exchanged between soils and water bodies. Instead, it is biogeochemically dynamic, transforming the materials that flow through the system, and interactive with the broader domain in which it is embedded. Characterizing these TAIs are steep process gradients in spatially compressed zones, and the current limited understanding of these process dynamics often is inferred only by comparing measurements of fluxes into and out of the interfaces. This limited knowledge is a large source of uncertainty in global and regional models of carbon, environment, and climate, also significantly impeding the ability to couple models across traditional process and research domains in meaningful and robust ways. Because these interfaces are ubiquitously distributed globally, a fundamental understanding of the hallmark processes in TAIs is needed to extend site-specific observations to a more globally relevant knowledgebase. Gathering this data will enable integration of models across process domains, spanning spatial and temporal scales. For these reasons, TAI-focused research is a priority of the scientific community, both to advance the science and to improve the predictability of the Earth system.

Several identified research challenges will focus these efforts:

- **Global Accounting of TAI Distribution, State, and Stores of Carbon and Nutrients: A Scaling Challenge.** Despite the known importance of TAIs, there is (1) a lack of an accurate accounting of the location, size, and element inventory of TAI systems and (2) a basic but fundamental research need for an accurate global accounting of TAI carbon and nutrient stocks, fluxes, and transformations, which is a critical gap in representing these systems in models. The challenge applies across all types of TAIs and is critical to assessing the extent to which these diverse ecosystems currently serve as net sources or sinks of carbon and how they will respond to changing anthropogenic releases of carbon and future alterations to climate, environment, and land use. Experience dictates that the challenge of scaling TAI processes from fine-scale phenomena to robust regional, continental, and global inventories will require creative new ways of integrating plot-scale, process-based research; landscape-scale, geospatially explicit databases; remote sensing; process-based numerical modeling; and creative new scaling concepts.
- **Coupling Processes Across Traditional Ecosystem Boundaries: A Transdisciplinary Challenge.** Traditionally, terrestrial, aquatic, and TAI ecosystems and processes have been the focus of separate scientific communities. This separation was due in part to the fact that many ecological and biogeochemical phenomena operate at different scales across systems, making quantification of their processes logistically and conceptually difficult. Similar challenges apply to the coupling of models that were designed to operate separately for terrestrial, TAI, or aquatic systems. Understanding processes across terrestrial-TAI-aquatic boundaries

also is fundamentally a challenge of scale. Processes that operate at small scales of time and space in TAIs drive large-scale phenomena that cannot be predicted with existing observational or modeling techniques. Advancing TAI science requires creative approaches to combining experiments, models, and observations that respect (rather than ignore) inherent differences in scale. Achieving this vision will require the development of scientific teams willing to work across traditional ecosystem boundaries and a cooperation across agencies that generally tend to focus funding on separate and different elements of the terrestrial-TAI-aquatic continuum.

- **Advancing a Predictive Understanding of Coupled Biogeochemical Cycles Through Improved Integration of Hydrologic, Geomorphic, Plant, and Microbial Processes.** Tremendous progress has been made over the past decades in understanding the biogeochemical feedbacks from biological and physical agents of change, including plants, microorganisms, hydrology, and geomorphology. This process-based understanding has advanced interactively through a combination of improved small- and large-scale observations, experimental manipulation, and numerical modeling. The result has been an improved capacity to understand and forecast change as illustrated by the increasing sophistication of Earth system models (ESMs), and TAIs represent the next big challenge in this evolution. Capturing crucial TAI processes in ESMs (and other models), requires bold new efforts to further integrate hydrology, plant biology, microbial ecology, and geomorphology in an Earth system context. Such efforts will need to account for (1) interactions between surface and groundwater as they move through TAI plant communities and soils; (2) changes in landscape structure resulting from sediment loss and gain; (3) the relationships between physiological and morphological plant traits and their responses to changes in oxygen availability, salinity, sediment deposition, warming, and other sources of plant stress; and (4) factors that regulate microbial community composition and microbial activities as they relate to reduction-oxidation potential and environmental gradients, including microbial processes in the plant rhizosphere.

- **Ecological and Biogeochemical Responses to Perturbations and Feedbacks on System Resilience.** Ecological and biogeochemical feedbacks tend to maintain ecosystems in a state of quasi equilibrium and, thereby, persist in landscapes for long periods of time. However, dramatic perturbations can exceed the capacity of ecosystems to recover and can lead to state changes (e.g., wetland to aquatic). A challenge for TAI science is to understand the features and processes that render ecosystems more or less resilient to spatial or temporal changes in external drivers such as hydrology, land use, climate, or sediment loads. Perturbations to such drivers arising from floods, droughts, fire, or sea level rise can affect TAIs both directly and indirectly via the terrestrial and aquatic systems to which they are coupled. Thus again, the challenge of scale is apparent because some perturbations occur at regular intervals (e.g., spring tide flooding) while other cases occur infrequently (e.g., hurricanes and wildfires). Clearly, the dynamics of human systems will need to be considered because of the immensity of their effects on key physical and biological processes. Understanding and predicting the impacts of perturbations (large and small) on TAIs require focusing on scale-relevant research and modeling.

APPENDICES

Appendix 1:
Federal Interagency Coordination and Collaboration

A Vision for Addressing Gaps in Terrestrial-Aquatic Interface Research

The findings discussed in this report from the September 2016 Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop clearly indicate that the terrestrial-aquatic interface (TAI) is a critical, complex system with important implications for natural and human processes and process interactions. The findings also demonstrate that gaps in current knowledge of TAIs are impeding the ability to predict the responses and feedbacks of these critical ecosystems to environmental changes and disturbances (e.g., land use, fire, and floods). Because improving the confidence in predictions involves an approach that combines model development with observations and field experiments, the prediction framework must be robust over all appropriate temporal and spatial scales. As such, advancing the state of the science of TAI ecosystems should employ approaches that directly feed and improve predictive models—an ambitious and urgent scientific grand challenge. This challenge to advance TAI science demands the application and integration of numerous scientific disciplines including biology, ecology, hydrology, modeling, sociology, chemistry, meteorology, and oceanography. Developing a predictive understanding of this complex system also requires careful integration and coupling of these disciplines and represents a unique opportunity to coordinate basic research among the scientific and federal research communities in ways that lead to positive outcomes for society.

The U.S. Department of Energy (DOE) has a long history of tackling grand challenges such as TAI research through large-scale field experiments [e.g., Free-Air CO_2 (carbon dioxide) Enrichment (FACE), Integrated Field Research Challenge, and Next-Generation Ecosystem Experiments], long-term observation campaigns (e.g., Atmospheric Radiation Measurement program and AmeriFlux Network), and complex efforts to model coupled Earth systems [e.g., Accelerated Climate Modeling for Energy (ACME)]. To address critical questions at the interface of energy and environment, DOE makes significant research investments in areas such as terrestrial ecosystems, subsurface biogeochemistry, Earth system modeling, genomics, and atmospheric science. However, the breadth and integrative nature of TAIs require a diversity of scientific disciplines that goes beyond those that involve only DOE.

The larger federal research community currently supports numerous activities that complement or interface with the transdisciplinary nature of TAI science, including the following examples.

- DOE and the U.S. Forest Service collaborate in providing support to the Spruce and Peatland Responses Under Climatic and Environmental Change Experiment (SPRUCE). SPRUCE is a decade-long experiment investigating the role played by artificially warmed air and soils on peatland carbon dynamics.
- The Smithsonian Institution operates the Global Change Research Wetland, a field facility dedicated to integrated, long-term (i.e., 30-year) manipulative experiments, observations, and modeling of carbon cycling in a coastal tidal marsh. Observations, remote sensing, and ecosystem-scale numerical models advance forecasts of impacts on coastal wetland processes of rising CO_2, nitrogen enrichment, invasive species, sea level rise, and warming.
- The National Science Foundation supports a number of Long-Term Ecological Research (LTER) sites that include TAIs such as the Plum Island Ecosystems LTER and the Virginia Coast Reserve LTER, as well as various Critical Zone Observatories and

future National Ecological Observatory Network sites that examine watershed-scale science.

- The U.S. Geological Survey has long supported a national stream gage network and has demonstrated growing interests in wetlands and studies of blue carbon.
- The U.S. Department of Agriculture has made numerous investments to understand ecosystem services provided by wetland and coastal systems as well as wetland mitigation practices relevant to agricultural systems.
- The National Aeronautics and Space Administration's Earth Sciences Division has demonstrated expertise in understanding ocean and aquatic biogeochemistry impacted by land processes observed from airborne and satellite platforms.
- The National Oceanic and Atmospheric Administration's National Estuarine Research Reserve System, as well as related coastal and ocean carbon programs, has focused on understanding the aquatic carbon cycle.
- Applied research and policy programs at the U.S. Department of Defense (e.g., Strategic Environmental Research and Development Program and U.S. Army Corps of Engineers) have focused on mitigating and regulating the impacts of disturbance events such as floods along rivers and the coastal margin.

This list is not exhaustive, but it does demonstrate a broad level of federally supported research seeking to understand and manage the interface between land and water.

Given this rich body of support for TAI science, opportunities exist whereby coordination across federal institutions could increase the scientific return of overall national investments. Robust understanding of the transdisciplinary, complex systems that include TAIs benefits tremendously from strategic coordination of, and collaborations involving, numerous federal agencies and stakeholders. With carefully coordinated research agendas, these complementary investments and objectives can decrease the time needed to achieve scientific breakthroughs and at the same time reduce unnecessary overlap and long development periods for new capabilities. The congressionally mandated U.S. Global Change Research Program provides an ideal example and venue where federal agencies interact, strategize, and implement coordinated research efforts that combine the interests and expertise of multiple federal research programs to tackle grand scientific challenges such as TAI research.

Although the TAI workshop focused on DOE and its specific mission, this report highlights a broader opportunity to coordinate future research efforts among multiple federal agencies and stakeholders. Recent workshops and meetings sponsored by federal and academic programs on, for example, TAIs, blue carbon, coastal ecosystems, ocean biogeochemistry, and wetlands have come to the same conclusion—the understanding of TAIs represents a significant gap in knowledge of the coupled Earth system. Careful collaborations across multiple agencies will enable the coordination of investments while reducing unnecessary duplication of effort and preserving each agency's mission areas. Ultimately, this will result in a robust and comprehensive understanding of, and predictive capability for, TAIs that will be useful both to advance the science and to provide important information to stakeholders and policymakers for making informed decisions that involve these complex ecosystems.

Appendix 2: Agenda

Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop

September 7–9, 2016

Hilton Washington, D.C./Rockville Hotel

1750 Rockville Pike, Rockville, MD 20852

Day 1: Wednesday, September 7

7:30–9:00 a.m.	**Breakfast**		
9:00–9:40 a.m.	**Welcome and Introductory Comments** (Eisenhower Room)		
9:00 a.m.–9:05 a.m.	Welcome		J. DeForest
9:05 a.m.–9:15 a.m.	Climate and Environmental Sciences Division Interest in Terrestrial-Aquatic Interfaces (TAIs)		G. Geernaert
9:15 a.m.–9:20 a.m.	Role of Workshop Reports		D. Stover
9:20 a.m.–9:30 a.m.	Scope and Workshop Charge		J. DeForest
9:30 a.m.–9:40 a.m.	Breakout Logistics and Initial Questions and Answers		J. DeForest, Workshop Organizers
9:40–10:10 a.m.	**Plenary Sessions** (Eisenhower Room)		
9:40 a.m.–9:50 a.m.	An Overview of TAIs		P. Megonigal
9:50 a.m.–10:20 a.m.	Current State and Needs of TAI Modeling		R. Leung, W. Riley, P. Thornton
10:20 a.m.–10:30 a.m.	Geomorphology and Landscape Dynamics		J. Rowland
10:30 a.m.–10:40 a.m.	Ecosystem Carbon Cycling in TAIs		P. Raymond
10:40 a.m.–10:50 a.m.	Major Disturbance in TAIs		T. Troxler
10:50 a.m.–11:00 a.m.	**Break**		
11:00 a.m.–1:15 p.m.	**Breakout Sessions**		
11:00 a.m.–1:00 p.m.	**Breakout Session Topic 1: Physical Processes**		
	Group A: (Monroe Room)	Lead: V. Bailey	Rapporteur: E. Coon
	Group B: (Jackson Room)	Lead: J. Rowland	Rapporteur: P. Raymond
	Group C: (Lincoln Room)	Lead: P. Megonigal	Rapporteur: H. Diefenderfer
1:00 p.m.–1:15 p.m.	**Summarizing Group Discussion for Rapporteurs**		
1:15 p.m.–2:15 p.m.	**Working Lunch and Interaction Time** (Lobby, Eisenhower Room)		
1:45 p.m.–2:15 p.m.	**Breakout Session Reporting** (Eisenhower Room)		
2:15 p.m.–4:30 p.m.	**Breakout Sessions**		
1:45 p.m.–4:15 p.m.	**Breakout Session 2: Spatial and Temporal Heterogeneity**		
	Group A: (Monroe Room)	Lead: T. Troxler	Rapporteur: E. Canuel
	Group B: (Jackson Room)	Lead: J. Rowland	Rapporteur: P. Thornton
	Group C: (Lincoln Room)	Lead: P. Megonigal	Rapporteur: A. Langley
4:15 p.m.–4:30 p.m.	**Summarizing Group Discussion for Rapporteurs**		
4:30 p.m.–4:45 p.m.	**Break**		
4:45 p.m.–5:15 p.m.	**Breakout Session Reporting** (Eisenhower Room)		
5:15 p.m.–5:45 p.m.	**Open Discussion** (Eisenhower Room)		
5:45 p.m.	**Summary and Closing** (Eisenhower Room)		Workshop Organizers
6:00 p.m.	**Collaboration of Writing Teams**		Selected Members

Day 2: Thursday, September 8

7:30 a.m.–9:00 a.m.	**Breakfast**		
9:00 a.m.–9:10 a.m.	**Welcome and Reconvening Comments** (Eisenhower Room)		
9:00 a.m.–9:10 a.m.	Welcome and Comments		Workshop Organizers
9:10–9:50 a.m.	**Plenary Session** (Eisenhower Room)		
9:10 a.m.–9:20 a.m.	Research Opportunities at the Critical Zone Observatories		W. McDowell
9:20 a.m.–9:30 a.m.	Microbial Controls on Biogeochemical Processes in TAIs		K. Wrighton
9:30 a.m.–9:40 a.m.	Fine-Scale Processes		V. Bailey
9:40 a.m.–9:50 a.m.	Process Scaling from Fine to Landscape Scales		S. Fendorf
10:00 a.m.–12:15 p.m.	**Breakout Sessions**		
10:00 a.m.–12:15 p.m.	**Breakout Session 3: Biogeochemical and Ecological Processes**		
	Group A: (Monroe Room)	Lead: V. Bailey	Rapporteur: S. Fendorf
	Group B: (Jackson Room)	Lead: T. Troxler	Rapporteur: M. Mayes
	Group C: (Lincoln Room)	Lead: P. Megonigal	Rapporteur: M. Newcomer
12:00 p.m.–12:15 p.m.	**Summarizing Group Discussion for Rapporteurs**		
12:15 p.m.–1:15 p.m.	**Lunch**		
12:45 p.m.–1:15 p.m.	**Breakout Session Reporting** (Eisenhower Room)		
1:15 p.m.–4:00 p.m.	**Breakout Sessions**		
1:15 p.m.–3:30 p.m.	**Breakout Session 4: Future Directions**		
	Group A: (Monroe Room)	Lead: V. Bailey	Rapporteur: B. Benscotter
	Group B: (Jackson Room)	Lead: T. Troxler	Rapporteur: J. Stegen
	Group C: (Lincoln Room)	Lead: J. Rowland	Rapporteur: A. Langley
3:15 p.m.–3:30 p.m.	**Summarizing Group Discussion for Rapporteurs**		
3:30 p.m.–4:00 p.m.	**Breakout Session Reporting** (Eisenhower Room)		
4:00 p.m.–4:15 p.m.	**Break**		
4:15 p.m.–4:45 p.m.	**Open Discussion** (Eisenhower Room)		Workshop Organizers
4:45 p.m.–5:15 p.m.	**Synthesizing the Major Themes** (Eisenhower Room)		Workshop Organizers
5:15 p.m.–5:30 p.m.	**Summary and Closing** (Eisenhower Room)		Workshop Organizers
5:30 p.m.	**Collaboration of Writing Teams**		Selected Members

Writing Day: Friday, September 9

Appendix 3: Workshop Breakout Questions

The purpose of the breakout sessions is to determine the state of the science and the most important and pressing research priorities that would lead to significant improvements to a predictive understanding of terrestrial-aquatic interfaces (TAIs) in the context of climate and environmental forcings. Importantly, the U.S. Department of Energy (DOE) is interested in discovery science that strengthens models by bridging gaps in the process-level understanding of phenomena that drive changes in the Earth system.

Day One

1. Physical Processes

a. Which physical processes and dynamics are most important to capture in models designed to forecast changes in TAIs? In the coupling between TAIs and adjacent systems?

b. What are the thresholds at which changes in hydrology, sediment dynamics, sea level, land-use change, or other physical drivers force TAIs across biogeochemical or ecological thresholds to cause state change?

c. Given DOE's aim to improve the performance of Earth system models (ESMs), which TAIs, or processes that may unify TAIs, are most poorly understood? Why? Which TAIs do models most poorly represent?

d. Which model structures and modeling gaps must be prioritized to capture key spatial and temporal scales that regulate TAI physical processes?

2. Spatial and Temporal Heterogeneity

a. Which disturbances, perturbations, or climatic extreme events in TAIs, both in space and time, most fundamentally alter TAI function?

b. How can scientists recognize and quantify system thresholds, particularly when they operate across large spatial and temporal scales that require expertise across disciplines such as hydrological and ecosystem-climate feedbacks?

c. What is the current state of models in terms of capturing relevant spatial and temporal variabilities, especially as these differences relate to disturbances or perturbations?

d. What are the critical needs for improving multiscale observations and modeling in TAIs to improve the understanding of their spatial and temporal heterogeneities?

Day Two

3. Biogeochemical and Ecological Processes

a. What are the dominant controls on changes in plant traits, plant community dynamics, and plant ecophysiologies in TAIs, especially those that are relevant to ecosystem function, ecosystem-climate feedbacks, and ESMs?

b. Which properties of microbial communities and which of their processes are relevant to the key biogeochemical processes that distinguish TAI ecosystems?

c. What are the thresholds at which biological, biogeochemical, ecological, and ecosystem dynamics lead to system-relevant state changes?

d. Which model structures and modeling gaps must be prioritized to capture the relevant spatial and temporal scales that regulate biological and biogeochemical processes of TAIs?

4. Future Directions

a. Which human activities fundamentally affect the relevant physical, biological, and biogeochemical processes in TAIs? Which of them are most relevant for the biogeochemical coupling of TAIs to adjacent ecosystems or Earth systems?

b. What are the biggest challenges to linking TAI-relevant physical and biological processes in terms of both observations and modeling?

c. What combination of observations, experiments, and facilities are needed to parameterize multiscale models to improve the predictive understanding of TAIs in the Earth system?

d. What topics did we miss?

Appendix 4: Workshop Participants

Fig. 17. Workshop Participants. Participants of the Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models Workshop.

Co-Chairs

Vanessa Bailey
Pacific Northwest National Laboratory

Patrick Megonigal
Smithsonian Environmental Research Center

Joel Rowland
Los Alamos National Laboratory

Tiffany Troxler
Florida International University

Participants

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Elizabeth Canuel
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Valerie Ivanov
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Sujay Kaushal
University of Maryland

Ken Kemner
Argonne National Laboratory

Randall Kolka
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Kevin Kroger
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Ruby Leung
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Rebecca Neumann
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Michelle Newcomer
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Christopher Osburn
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Peter Raymond
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Daniel Ricciuto
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Sharlene Weatherwax
Associate Director for Science

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Kathy Hibbard
National Aeronautics and Space Administration

Laura Lorenzoni
National Aeronautics and Space Administration

Hank Margolis
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Karina Schaefer
National Science Foundation

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U.S. Geological Survey

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Acronyms and Abbreviations

3D	three-dimensional
ACME	Accelerated Climate Modeling for Energy
ALM	ACME Land Model
BER	DOE Office of Biological and Environmental Research
CDOM	colored dissolved organic matter
CESD	BER Climate and Environmental Sciences Division
CH_4	methane
CLM	Community Land Model
CO_2	carbon dioxide
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
DOE	U.S. Department of Energy
DOM	dissolved organic matter
ESM	Earth system model
HRM	hyper-resolution model
IPCC	Intergovernmental Panel on Climate Change
LTER	Long-Term Ecological Research
MIP	Model Intercomparison Project
NEON	National Ecological Observatory Network
NO_3	nitrate
N_2O	nitrous oxide
NutNet	Nutrient Network
RANS	Reynolds-averaged Navier-Stokes (an equation)
redox	reduction-oxidation
ROM	reduced-order model
SO_4^{2-}	sulfate
SOC	soil organic carbon
SOM	soil organic matter
SPRUCE	Spruce and Peatland Responses Under Climatic and Environmental Change
TAI	terrestrial-aquatic interface
TES	CESD Terrestrial Ecosystem Science program

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Chapter 1: Large thermokarst along the Selawik River in Northwest Alaska. Courtesy Oak Ridge National Laboratory. **Chapter 2:** Flooded region of Kirkpatrick Marsh on the Chesapeake Bay in Maryland. Courtesy Patrick Megonigal, Smithsonian Environmental Research Center. **Chapter 3:** Tidal freshwater marsh near the mouth of the Columbia River in Washington. Courtesy Amy Borde, Pacific Northwest National Laboratory. **Chapter 4:** Riparian vegetation and sediments adjacent to the Columbia River in Washington. Courtesy Amy Goldman, Pacific Northwest National Laboratory. **Chapter 5:** Tiveden National Park, Sweden. Courtesy iStock Photo. **Chapter 6:** Section of river bank from the East River, near Crested Butte, Colorado. Courtesy Joel Rowland, Los Alamos National Laboratory. **Chapter 7:** Travis Spit near Sequim, Washington, at low tide. Courtesy Charles Brandt, Pacific Northwest National Laboratory. **Appendices:** Black spruce forest in the Caribou-Poker Creeks Research Watershed, Alaska. Courtesy Carolyn Anderson, Pacific Northwest National Laboratory.