PNNL-28635

STAR Workshop

Terrestrial–Aquatic Research in Coastal Systems

April 2019

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

From September 24–26, 2018, Pacific Northwest National Laboratory hosted a System for Terrestrial–Aquatic Research (STAR) workshop to discuss terrestrial–aquatic interface (TAI) research needs. The purpose of this workshop was to continue discussion initiated at the 2016 Department of Energy (DOE)-Biological and Environmental Research (BER) workshop: *Research Priorities to Incorporate Terrestrial–Aquatic Interfaces in Earth System Models*. Specifically, this workshop focused on terrestrial–aquatic interfaces near the coastline, which have been identified as a major gap in Earth system models (ESMs) and observational networks, important ecosystems that are vulnerable to disturbances from both the land and sea, as well as hubs for human habitation and commerce.

Through a variety of oral presentations and interdisciplinary working groups, the workshop participants aimed to address the following questions:

- What data types and observations specific to the interactions within a coastal TAI ecosystem are needed to improve process understanding and representation in next generation ESMs?
- What type of baseline measurements are needed to better understand the impact of dynamic processes?
- What network of measurements and observations is needed to resolve fundamental processes, as well as capture the impact of disturbances and extreme events, which impact these ecosystems on short, mid, and long timescales?
- What advancements are needed in instrumentation and technology for making the measurements proposed? What are some critical measurement gaps?
- Could an integrated network of stationary and mobile sites be developed to answer the above questions? What might such a network look like? Are there other network configurations we should consider?

Summary of Findings

A predictive and quantitative understanding of material and energy fluxes across TAI boundaries, and the material and energy transformations within boundaries, is needed to robustly represent these exchanges in Earth system models. Such understanding must encompass the two-way exchange of energy, water, and chemicals between land, estuary, and ocean—requiring multidisciplinary and transdisciplinary science. We must understand and couple biological, chemical, geomorphological, and physical processes in order to represent and predict key exchanges and transformations, and their responses to agents of perturbation and change. Carbon responds strongly to each of these phenomena and can serve as a common way to link processes across biological domains, chemical definitions, and physical locations.

A notable workshop finding was the recognition that coastal TAI and associated processes are significantly underrepresented in current ESM models (described in Section 4.0). Two approaches to addressing this were considered: (1) modification of existing models in novel, TAI-informed ways, and (2) development of new models tailored to coastal TAIs. Either approach is intricately tied to scaling and should be informed by both top-down (ESM grid-scale) and bottom-up approaches (process definitions and development of reduced-order models).

Finally, there was enthusiastic agreement on the need for a coordinated network of research sites that includes monitoring baseline conditions and experimentation to accelerated process discovery.

Acknowledgments

We would like to thank all workshop participants for their thoughtful contributions and DOE for continued support of fundamental science.

Front Row (L to R): Nancy Hess, Rodrigo Vargas, Miguel Goni, Nick Ward, Pat Megonigal, Neil Kamal Ganju, Jay Jones. Middle Row (L to R): Emmet Duffy, Nate McDowell, Yilin Fang, Aditi Sengupta, Lihini Aluwihare, Elizabeth Canuel, Maria Tzortziou, Pamela Weisenhorn, Roser Matamala, Rebecca Neumann, Jesse Vance, David Butman, Tarang Khangaonkar. Back Row (L to R): Lisamarie Windham-Myers, Charles Hopkinson, James Morris, Emily Graham, Chris Osburn, Adam Langley, René M. Price, Joel Rowland, Peter Thornton, Gautam Bisht, Heida Diefenderfer.

Acronyms and Abbreviations

BER	Biological and Environmental Research program
BGC	Biogeochemical
CCARS	Coastal CARbon Synthesis
CDR	Carbon dioxide removal
C-GEMS	Carbon-Generic Estuary Model
CMS	Carbon Monitoring System
COMPAS	Coastal Ocean Marine Prediction Across Scales
COMT	Coastal Ocean Modeling Testbed
CSIRO	Commonwealth Scientific and Industrial Research Organization
DNDC	Denitrification-Decomposition
E3SM	Energy Exascale Earth System Model
ESM	Earth system model
FACE	Free-Air CO_2 Enrichment
MOSART	MOdel for Scale Adaptive River Transport
MPAS	Model for Prediction Across Scales
NEON	National Ecological Observatory Network
NGEE	Next Generation Ecosystem Experiments
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PNNL	Pacific Northwest National Laboratory
ROMS	Regional Oceanic Modeling System
SERC	Smithsonian Environmental Research Center
SET	Surface/soil/sediment elevation/erosion table
SLR	Sea-level rise
SOCCR2	Second State of the Carbon Cycle Report
SPRUCE	Spruce and Peatland Responses Under Changing Environments
STAR	System for Terrestrial-Aquatic Research
TAI	Terrestrial-aquatic interface
WETCARB	Wetland-Estuary Transports and CARbon Budgets

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1.0 Workshop Summary, Purpose and Objectives

Terrestrial–aquatic interfaces (TAIs) represent a small portion of the Earth's surface, but are believed to have a disproportionately large impact on the release of greenhouse gases (e.g., CO_2, CH_4, and N_2O) to the atmosphere and the discharge of dissolved organic carbon and nutrients to coastal marine ecosystems.[1] The processes that drive these biogeochemical fluxes at this interface are poorly represented in current Earth system models (ESMs), partly because of the scales at which they take place and partly because they occur at the boundary of ecosystems that are traditionally studied independently. The terrestrial–aquatic interface is characterized by biogeochemical dynamism, high ecological/economic value, and vulnerability to extreme events. A better understanding of the transformational capacity of these dynamic terrestrial–aquatic ecosystems is important to enable a more accurate prediction of Earth system responses and resilience to extreme events.

In September 2016, the U.S. Department of Energy (DOE) Biological and Environmental Research (BER) program held a workshop highlighting research needs to address major scientific challenges in advancing the representation of TAIs in ESMs to improve their predictive capacity.[2] TAIs are driven by unique hydrology, vegetation, and greenhouse gas exchanges that do not exist in the modeling frameworks currently used for global simulations. Recommendations from that workshop point to the need for a focused program of linked observations and models that target the interactions among plant, soil, and hydrologic processes driving hydro-biogeochemical spatial gradients and temporal variation across and within terrestrial–aquatic ecosystem interfaces and boundaries. A diversity of experimental sites is important to ensure that the fundamental understanding of these sensitive ecosystems can be captured and applied to the broader principles of their roles in carbon and nutrient cycling. A recent BER Grand Challenges report states that, "…advances in modeling will require measurements for the coupled Earth system," and that "…measurements of terrestrial, coastal and cryosphere systems have significant gaps."[3]

Pacific Northwest National Laboratory (PNNL) uses its leadership role within DOE, and the larger scientific community, to advance the understanding and modeling of complex Earth system processes and systems dynamics. A major laboratory objective is to enhance our scientific leadership by advancing the understanding of the key atmospheric, biogeochemical, plant-microbe, and hydrologic processes affecting coastal, wetland, and riverine systems and their feedback to the Earth system. In addition, PNNL stewards DOE's Marine Sciences Laboratory in Sequim, WA, which provides a unique platform for developing and testing needed instrumentation and/or experimental approaches for new types of measurements in these dynamic and spatially heterogeneous ecosystems.

In support of this leadership role, PNNL hosted a two-and-a-half-day workshop in late September 2018 with a specific focus on coastal terrestrial–aquatic ecosystems, including Earth system and process modeling, ecosystem science, hydrology, and biogeochemistry expertise. This workshop—with attendees from academic, national laboratory, and other government agency institutions—explored the critical data, observations, and experiments required to understand fundamental processes important in coastal terrestrial–aquatic ecosystems. Driven by the science needs and priorities of DOE Earth system models,

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[1] Mcleod E, GL Chmura, S Bouillon, R Slam, M Bjork, CM Duarte, CE Lovelock, WH Schlesinger, and BR Silliman (2011). A Blueprint for Blue Carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Front Ecol Environ* 2011 9:552-560, doi:10.1890/110004.

[2] U.S. DOE (2017). *Research Priorities to Incorporate Terrestrial-Aquatic Interfaces in Earth System Models: Workshop Report*, DOE/SC-0187, U.S. Department of Energy Office of Science. tes.science.energy.gov.

[3] U.S. DOE (2017). *Grand Challenges for Biological and Environmental Research: Progress and Future Vision*, DOE/SC-0910, U.S. Department of Energy Office of Science. science.energy.gov.

as well as gaps in our understanding of coupled Earth system processes, the workshop also addressed potential facility design elements needed to deliver the data, observations, and process understanding required to address this critical problem. PNNL recognizes this is an area of interest to multiple agencies. The outcomes of this workshop will help to identify the unique role that DOE can bring to this area of science—ultimately leveraging key partnerships with ongoing national activities funded by the Smithsonian Institute, National Oceanic Atmospheric Administration, National Science Foundation, and others.

Workshop objectives addressed the following questions:

1. What data types and observations specific to the interactions within a coastal TAI ecosystem are needed to improve process understanding and representation in next generation ESM? The focus will be on data, observations, and experiments that are not currently being acquired by other networks, or that can readily supplement existing data.
2. What type of baseline measurements are needed to better understand the impact of dynamic processes?
3. What suite of measurements and observations is needed to resolve fundamental processes, as well as capture the impact of extreme events, which impact these ecosystems on short, mid, and long timescales?
4. What are some critical measurement gaps? Do we have the instruments and technology for making the measurements needed?
5. Could an integrated network of stationary and mobile sites be developed to answer the above questions? What might such a network look like? Are there other network configurations we should consider?

2.0 Workshop Introduction: Coastal Terrestrial–Aquatic Interfaces and Earth System Modeling

Presentation by Nick Ward and Pat Megonigal

Earth System Modeling

For decades, DOE-BER has funded studies focused on improving terrestrial ESMs through the explicit coupling of experiments, observations, and model development. Through BER's recognition that understanding Earth processes require working across many scales, from microbes to global systems, ESMs have increased in sophistication with each new study and research program.

In the mid-1990's, BER designed and implemented the successful Free-Air CO_2 Enrichment (FACE) studies. Initially, FACE experiments were focused in temperate forests because they cover large areas, were poorly represented in ESMs at the time, and are an important variable in climate regulation. BER used this same strategy when it launched the Next Generation Ecosystem Experiments (NGEE) program—tackling new ecosystems that are spatially extensive and globally important regulators of biogeochemical processes, such as northern peatlands, terrestrial arctic ecosystems, and tropical forests. This diversified approach to studying systems includes experimental manipulations such as the Spruce and Peatland Responses Under Changing Environments (SPRUCE) project (which uses a scalar approach), NGEE Arctic terrestrial studies (which use a landscape modeling approach), and NGEE Tropics studies (which use a distributed site approach). See Figure 2.1 for photos from these projects.

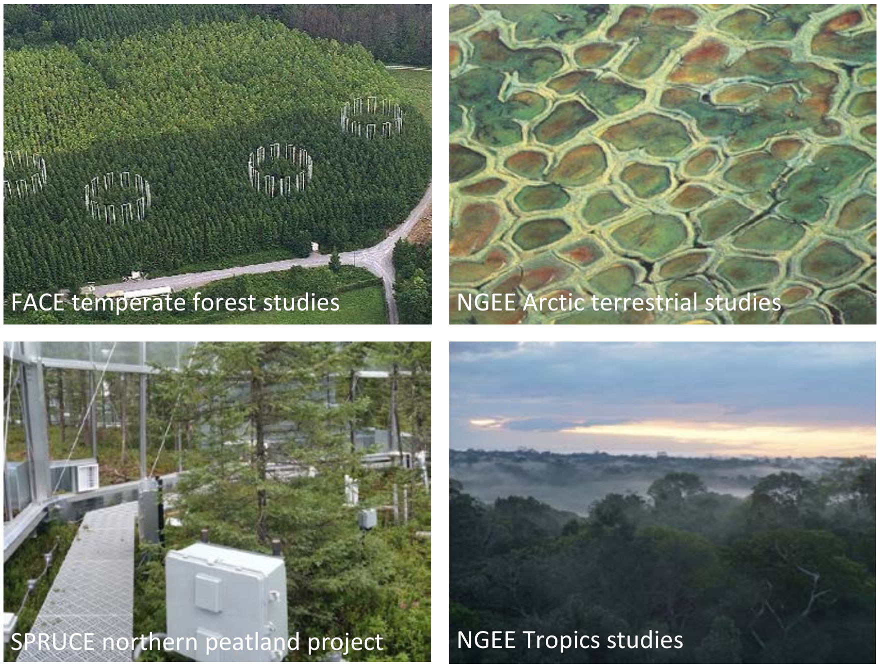

Figure 2.1. Photos from DOE BER-funded research that acquire data for the refinement of predictive Earth system models.

The next major challenge to improving ESMs is the incorporation of terrestrial edge data. This feat is particularly difficult because ESM development is currently approached as separate terrestrial, oceanic, and atmospheric domains. TAIs are not defined as a geographic location or ecosystem type in the way program boundaries of federal and state agencies, and other interests, are often defined.

Terrestrial–Aquatic Interfaces

Terrestrial–aquatic interfaces (TAIs) are characterized by hydrobiogeochemical interactions occurring across highly compressed temporal and spatial scales, and they influence global cycles far more than expected based on the proportion of the land surface they occupy. Research at the TAI is challenging because of extreme spatial and temporal variation caused, in part, by strong gradients in their biological and physical processes. These gradients create hotspots and hot moments of biogeochemical activity that will be particularly challenging to resolve. A better understanding of the transformational capacity of these dynamic terrestrial–aquatic ecosystems is important to enable more accurate prediction of Earth system response and resilience in the face of extreme events. However, the processes that drive these biogeochemical fluxes at this interface are poorly represented in current ESMs, partly because of the scales at which they take place and partly because they occur at the boundary of ecosystems that are traditionally studied independently.

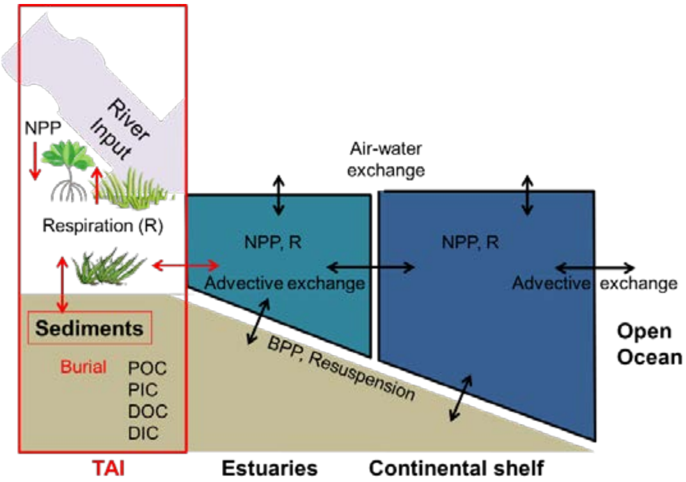

Figure 2.2. Model of coastal dynamics. Modified from Najjar et al. (2018) by L. Windham-Myers and P. Megonigal.

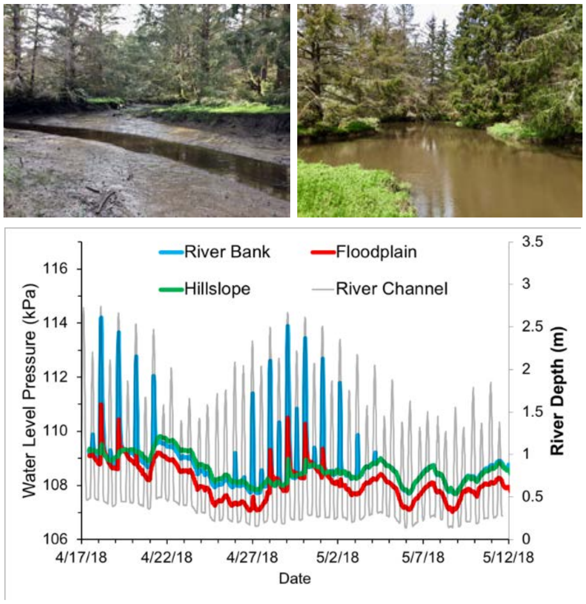

Figure 2.3. Pacific Northwest coastal site with high tidal variability. Groundwater level also varies tidally, and this signal diminished from the river bank to the hillslope. Extreme high tides inundate the entire floodplain landscape. Photos and data courtesy Nicholas Ward (unpublished).

Coastal TAIs

The boundary of a coastal TAI occurs between the head tides, the upstream boundary of tidal influence on hydrologic flows, and the head of the sea, where purely marine processes dominate (see Figure 2.2).[4] As coastal TAIs are influenced by tides and upstream dynamics, an important reason to study these interactions is to understand how they, in turn, influence estuaries and the near-sea environment. For example, the tidal portion of the Amazon River reaches 800 km inland, amounting to more than 10% of the whole drainage basin's surface area. The tidally-influenced reaches of the river emits nearly the same amount of CO_2 as the entire upper river due to its large surface area and long fetch (Sawakuchi et al. 2017).[6]

The flow of water to and from the landscape underlies key processes between the upland, supratidal, intertidal, and subtidal areas. A challenge in modeling tidal systems is describing the two-way transfer between water and land and the impact on biogeochemical activity. Figure 2.3 demonstrates an example from a Pacific Northwest

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[4] Najjar, R. G., Herrmann, M., Alexander, R., Boyer, E. W., Burdige, D. J., Butman, D., et al (2018). Carbon budget of tidal wetlands, estuaries, and shelf waters of eastern North America. *Global Biogeochemical Cycles*, 32, 389–416. doi:10.1002/2017GB005790.

site, with extreme tidal variability, where groundwater levels are influenced by tides more than 100m inland from the river channel even though the soils are not very permeable. Similar tidal variability is seen in biogeochemical parameters, such as salinity, CO_2, and pH (Ward unpublished).

A second reason for studying TAIs is to understand how they connect and fundamentally influence larger systems. Many of the most familiar examples of TAIs concern gradients in hydrology, sediments, and organisms. Though traditionally less studied, TAIs play an important role in atmospheric processes, such as CO_2 and CH_4 emissions from tidal rivers and wetlands. For example, research by Chris Loughner and workshop attendee Maria Tzortziou, as well as others, shows how large-scale circulation patterns and emissions sources concentrate dry NO_3 deposition in the mid-Atlantic TAI (see Figure 2.4).[5] This pattern had not been previously observed because both models and observation networks were too coarse to detect the phenomenon. This highlights the importance of multi-organizational partnerships and collaborations designed to increase the resolution at which we observe and model TAI processes.

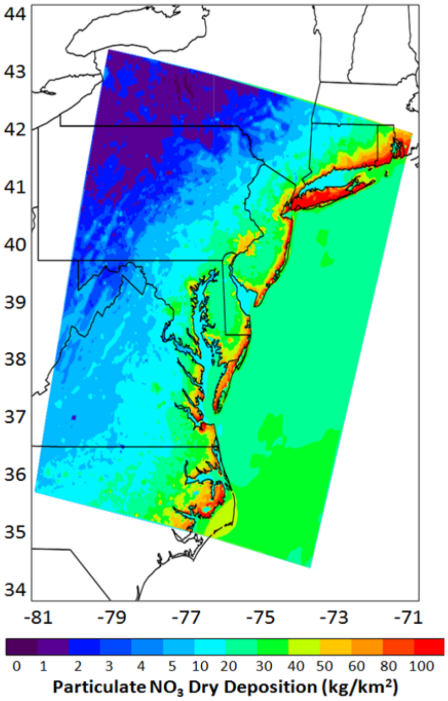

Figure 2.4. Demonstrates how large-scale circulation patterns and emissions sources concentrates dry NO_3 deposition in the mid-Atlantic TAI. Loughner and Tzortziou et al. 2016.

Processes occurring along these types of tidally-influenced ecosystems have not been adequately incorporated into global carbon budgets. For example, including the tidal portion of the Amazon River, alone, in global estimates of inland water CO_2 emissions increases this evasive flux by up to 40%, implying that emissions from rivers and lakes nearly balance net terrestrial uptake of anthropogenic CO_2 emissions (Sawakuchi et al. 2017).[6] Though similar evaluations of other systems—big and small—have only recently begun, researchers are already able to recognize quasi-universal processes occurring globally. For example, biogeochemical activity in tidal rivers appear to be driven by processes such as storm events, tides, seasonal discharge, and mixed variables of light, tides, and seasons (Ward and Indivero 2018).[7]

Workshop Goal

How can DOE resources and expertise be leveraged most effectively to address data and model gaps at the coastal TAI?

Clarifying questions:

- What data types and observations, specific to terrestrial–aquatic coastal ecosystems, are needed to improve process understanding and representation in next generation ESMs?

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[5] Christopher P Loughner, Maria Tzortziou, Shulamit Shroder, Kenneth E Pickering (2016). Enhanced dry deposition of nitrogen pollution near coastlines: A case study covering the Chesapeake Bay estuary and Atlantic Ocean coastline. *Journal of Geophysical Research*. Vol.121(23), p.14,221-14,238. doi:10.1002/2016JD025571.

[6] Sawakuchi, et al. (2017). Carbon dioxide emissions along the lower amazon River. *Frontiers in Marine Science*. 4, 76. doi:10.3389/fmars.2017.00076.

[7] Ward, N.D. and Indivero, J. (2018). High-resolution biogeochemical monitoring along three types of coastal interface ecosystems in the Pacific Northwest. Goldschmidt 2018. Boston, MA. 8/15/18.

- What baseline measurements are needed to understand the impact of dynamic processes?
- What suite of measurements and observations is needed to explore fundamental processes, as well as capture the impact of extreme events, which impact these ecosystems on short, mid, and long timescales?
- What are some critical measurement gaps? Do we have the instruments and technology for making the measurements proposed?
- Do we have the instruments and technology for making the measurements proposed?
- Is an integrated network of stationary and mobile sites one possible approach for designing an operational research facility to answer the above questions? What might such a network look like? Are there other network configurations we should consider?

3.0 Importance of TAI from an Ecological and Functional Perspective

Presentation by Vanessa Bailey

The Nexus of Where Land–Water–Atmosphere–People Intersect is a Critically Important Area to Study

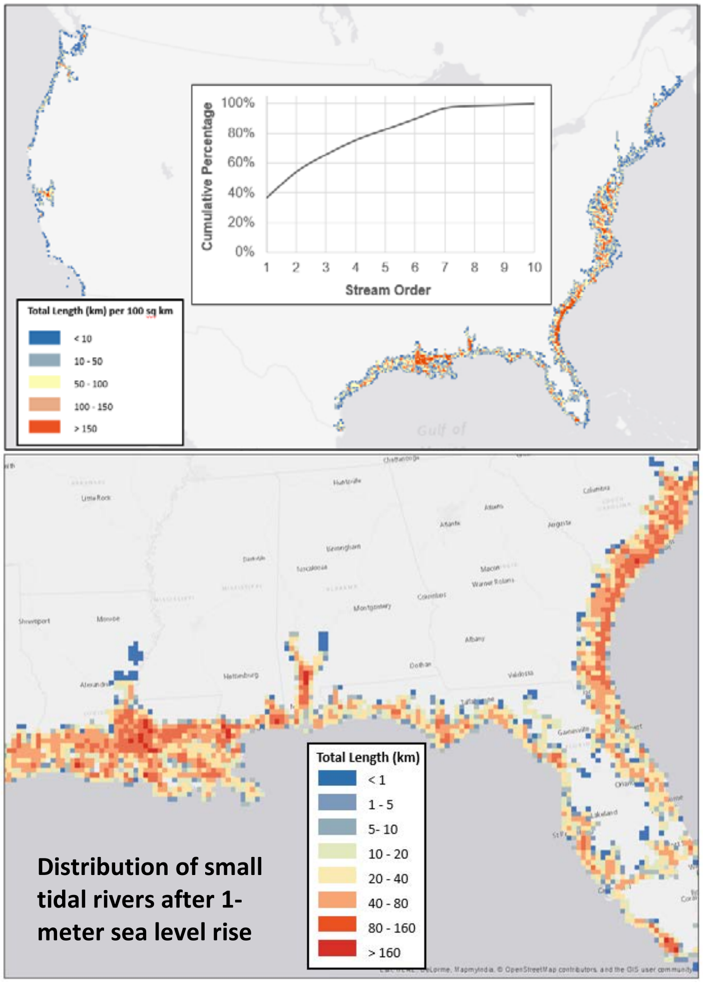

Figure 3.1. This map shows the distribution and length of tidal rivers around the US. The plot shows the cumulative percentage of tidal river length per stream order, indicating that nearly 40% of tidal rivers are first order streams. (courtesy J. Tagestad)

Terrestrial–aquatic interfaces (TAIs) are a critically important system defined by physical interactions between land and water that shape biogeochemical transformations and landscapes in response to both terrestrial and aquatic influences. Coastal systems affect human, energy, ecosystem, and economic security—they impact global nutrient budgets, affect millions of people, and cost trillions of dollars in disaster recovery (Canuel et al. 2012).[8] Water connects earth biomes and drives biogeochemical cycling, moving constituents in and out of ecosystems. The nexus of where land–water–atmosphere–people intersect is a critically important but understudied component of the Earth system. The flow of water is fundamental to the behavior of TAI systems. Carbon is the most fundamental element linked to TAI biogeochemical cycles, and can be used as an indicator of constituents entering and exiting TAI ecosystems. However, TAIs have largely been avoided in ESMs, as they do not behave predictably, and because of the many process uncertainties that exist where rivers meet seas.

Current Gaps in TAI Understanding

Where are the important gaps in understanding these systems and what is the spatial and temporal scale of these gaps? Should research focus on big rivers, the multitude of little rivers, or both? Approximately 40 million people live in tidal river domains, where

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[8] Canuel, E. A., Cammer, S. S., McIntosh, H. A., and Pondell, C. R. (2012). Climate change impacts on the organic carbon cycle at the land-ocean interface. *Annu. Rev. Earth Planet. Sci.* 40, 685–711. doi: 10.1146/annurev-earth-042711-105511.

there is an abundant assemblage of short rivers. With sea-level rise, the distribution of these tidal rivers changes sharply (see Figure 3.1). Research needs in this area include the following:

- Understanding how storms impact the system
- Predicting which direction terrestrial–aquatic boundaries will move
- Learning how microbial and chemical transformations and behaviors will be impacted by large-scale disturbances.

Need to Identify TAI Research Focus

Research needs to focus on understanding the drivers and resistance/resilience of coastal TAI ecosystems. System behavior, importance of drivers, sources of forcing, and couplings should be nested at different scales up to the Earth system. In order to predict coastal TAI response to perturbations, researchers need to know the fluxes through this interface, the resilience of these ecosystems, and the short-and long-term spatial migration of these interfaces. A focus on carbon cycling is needed as transformations of this life-linked element connect all facets of TAI systems, providing sensor and scalar data for ecosystem function.

TAI Data Incorporation into ESMs

Currently, coastal TAIs are not represented in ESMs. Further information is needed to couple ocean, terrestrial, and atmospheric models to represent TAI processes. In order to do that, researchers need a better understanding of the processes and feedbacks linking TAIs to adjacent systems. How can this coupling of natural, managed, and human systems be represented in ESMs? Are there ecosystem characteristics that translate into increased or decreased system resilience, such as the return intervals of events, physical impacts to the system, and the type of stressors? Estuaries are a key boundary system that should be considered in TAI-scaled models because they are both sources and sinks of carbon and other nutrients mediated by suspended sediments and tidal waters.

4.0 Coastal TAIs from a Modeling Perspective: Toward Representation in Earth System Models

Presentation by Peter Thornton

Summary of Presentation

Must decide what data to include in coastal TAI ESMs

The objective of ESMs is to improve prediction of the Earth's future climate. It requires information on a global scale, sensor input for parameterizations into the future (or prognostic modeling), data from multiple systems (atmosphere, ocean ice, land), and data from multiple coupling interfaces (atmosphere-land, atmosphere-ocean, land-ocean, etc.). To meet these requirements, researchers must decide on which processes should be explicit, which should be parameterized, and which can be ignored.

Figure 4.1 represents current Earth system modeling inputs and needs for modeling coastal TAIs. Both models include land, river, and ocean, including hydrologic transfer between systems. However, to include coastal TAIs into the next generation of ESMs, data from physical elements—such as upland, river, wetland, estuary, coastal ocean, and open ocean—need to be incorporated.

To accurately capture interface dynamics in next generation ESMs, the following elements need to be included:

- Process models for hydrodynamics, sediment and geomorphology, biogeochemistry, and ecology/vegetation
- System representations for carbon and nutrient cycles, greenhouse gas emissions, interactions with human systems of land and resource use, and environmental perturbations such as sea-level rise and storm surge.

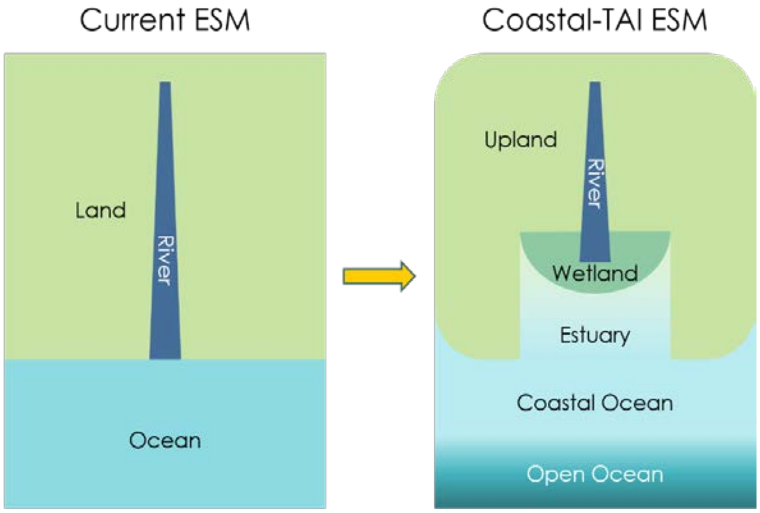

Figure 4.1. Comparison of current Earth system modeling with the modeling needs for coastal TAIs. Courtesy Peter Thornton (unpublished).

The next generation of ESM will leverage existing model components into an integrated modeling framework for TAI, including the following:

- Open ocean/coastal ocean: Model for Prediction Across Scales (MPAS) adaptive mesh developed by Rowland; COMPAS mesh refinement used by the Commonwealth Scientific and Industrial Research Organization (CSIRO); and the Regional Oceanic Modeling System (ROMS) used by Rutgers and UCLA
- Geomorphology models: idealized channel models like C-GEM to connect river to coast; models that incorporate river width and depth as a function from the river mouth

- Biogeochemistry: CSIRO models include sediment and BGC; Coastal Ocean Modeling Testbed (COMT) performed by NOAA models hypoxia
- Terrestrial hydrodynamics: CLM-SPRUCE models freshwater TAIs and includes segmentation based on microtopography, such as fen/bog mapping; Model for Scale Adaptive River Transport (MOSART) models land and river systems to connect tidal influence
- Vegetation: Marsh Elevation Models represent organic and inorganic material inputs as simple functions of vegetation growth as it responds to elevation and flooding duration. The models are informed by geomorphology and plant ecology
- Wetland biogeochemistry: A common model for wetland biogeochemistry is the poorly named "Denitrification-Decomposition" (DNDC) model which simulates many processes in addition to denitrification, including CH_4 emissions. There are also several models that specialize in CH_4 emissions, including the Wetland Extent and Wetland Methane Modeling (WETCHIMP) model.

Researchers can use E3SM for coastal TAIs

Using the Energy Exascale Earth System Model (E3SM), there are two ways wetlands can be represented spatially and functionally. The first option is to capture important system variances by creating a multi-level sub-grid representation of topographical units. This limits model complexity while including land units, columnar data, and plant functional types. The second option is to use exascale high-resolution coupling of full process-resolving models. This option is challenging because of computational limits and incomplete system knowledge, but the power to compute these models is nearly available.

Many components needed for ESM implementation of a coastal TAI module already exist. Now, the questions to answer include the following:

- What are the component-level gaps?
- What are the most effective approaches for component integration given our research priorities?
- What are the critical data gaps?

Summary of Workshop Discussion–Key Questions and Goals Addressed by Models of TAI

Key questions:

- What is the extent of wetland areas? It is difficult to measure from satellite imagery and determine the type of wetland.
- Can we use models to predict the location of current TAIs and understand the processes that drive their migration?
- What is the mass balance of carbon and other nutrients across the TAI?
- What is the impact of two-way transfer of energy, water, nutrients, and sediments at the ocean-land interface?

Future modeling should encompass and inform:

- Human dimensions
- Biogeochemical hotspots in space and time as well as feedbacks

- Knowledge of variable timescales and spatial extent of perturbations and processes in tidal wetlands
- Nested models with levels of complexity that inform larger scales using a minimum list of parameters:
  - Higher resolutions at local scales to determine non-linear processes
  - Parameterized/scaled physics for statistical scalability
  - Spatially adapted mesh at coastlines
- Better spatial and temporally resolved data to discover basic phenomena and build better nutrient and water budgets. We cannot fill this gap through direct measurement at present. We need strategies to simplify measurements with general principals, proxies, or co-variates.
- Better measurement of fluxes and explore the use of isotope tracking—radiocarbon and stable isotope approaches—to measure nutrient quantity. We should first focus on carbon, then potentially include nitrogen, sulfur, and other elements as needed.

5.0 Measurement Gaps Relevant to Modeling

Presentation by Lisamarie Windham-Myers

Summary of Presentation

Carbon is currency in earth processes

Carbon is the currency through which Earth system processes occur. The relevant carbon fluxes for coastal TAI research include gross primary production, ecosystem respiration, methane flux, tidal exchange (lateral flux), carbon burial, carbon sequestration, erosion and accretion, wetland extent change, and wetland elevation change. Multiple carbon tracking synthesis efforts are underway (see list below), but researchers need to focus on the data and measurement gaps missed by these efforts.

- CCARS, Coastal CARbon Synthesis
- NASA Blue CMS, Carbon Monitoring System
- NASA WETCARB, Wetland-Estuary Transports and CARbon Budgets
- SOCCR2, Second State of the Carbon Cycle Report
- National Academies of Sciences CDR, Carbon Dioxide Removal.

SOCCR2 concludes that land and coastal waters are net carbon sinks while everything else is a carbon source. About half of the carbon is lost between land and coastal waters. Terrestrial wetlands and tidal wetlands are exporting the same amount of carbon, though the extent of terrestrial wetlands is uncertain. For example, we cannot presently map where tidal rivers transition from saline to freshwater. It is unknown how much carbon is exported from inland coastal terrestrial and aquatic systems to tidal wetlands and estuaries. Because various carbon fluxes operate at different spatiotemporal scales, carbon budgets do not balance in short timeframes. This poses a challenge in coupling models when processes are occurring at different timescales.

Not all carbon is created equal

The relationship between soil carbon concentration (fraction per gram) and soil carbon density (fraction per volume) is similar across visually distinct wetland ecosystems, in part because carbon content and carbon density are strongly inversely correlated (Holmquist et al. 2018).[9] The range of carbon per gram in wetlands is small, indicating that climate has little effect on soil carbon stocks. Maximum gross primary production may also be similar across wetlands. However, geomorphic setting may be an important driver of carbon flux (Rovai et al. 2018).[10] Methane flux measurement is only problematic from a radiative forcing perspective at low salinity because there is less flux when systems are flooded with sulfate-rich water (Poffenbarger et al. 2011 revisited).[11] Is this as a result of the time of day, tide stage, or season when the measurements were made? Does methane also move out of the system by lateral transport? Is

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[9] Holmquist, J.R., Windham-Myers, L., Bliss, N., Crooks, S. (2018). Accuracy and Precision of Tidal Wetland Soil Carbon Mapping in the Conterminous United States. *Scientific Reports 8,* Article number 9478. doi: 10.1038/s41598-018-26948-7

[10] Rovai, Twilley, Castaneda-Moya, Riul, Cifuentes-Jara, Manrow-Villalobos, Horta, Simonassi, Fonseca, Pagliosa. (2018). Global controls on carbon storage in mangrove soils. *Nature Climate Change 8*, 534-538. doi: 10.1038/s41558-018-0162-5.

[11] Poffenbarger, Needelman, Megonigal. (2011). Salinity influence on methane emissions from tidal marshes. *Wetlands*. 31:831-842. doi:10.1007/s13157-011-0197-0.

methane production determined primarily by gross primary production, which is also strongly dependent on salinity.

Potential approaches for modeling TAI carbon fluxes

- Gross primary production—data tuned by cross-scale satellite models
- Ecosystem respiration—measurements must include lateral flux
- Methane flux—scale, methods, and mechanistic insights are critical
- Tidal exchange (lateral flux)—function of hydrology, geomorphology, and vegetation; needs to consider both dissolved forms and particles
- Carbon burial—can be modeled from sediment accretion data
- Carbon sequestration (stabilization)—can be modeled from microbially explicit models and digital elevation models of both land surfaces and water surfaces
- Erosion and accretion—geomorphic models and image validation
- Extreme events that cause erosion and deposition are important
- Wetland extent change—can be mapped at multiple scales (needs validation)
- Wetland elevation change—can be mapped at 5-year intervals.

Measurements needed to focus on the two-way interaction at TAIs

- Hydrodynamics—surface, sub-surface, ground water, and tidal intrusion; need to determine the temporal scale and the distribution on variance.
- Need to consider high-resolution spatial and temporal data scales to understand carbon budgets. Carbon quality is important. The relative contributions of allocthonous and autochthonous sources of major gas fluxes, as is the fate of carbon exported as dissolved or particulate matter. There is a need to measure multiple carbon pools using a standard protocol for comparative carbon measurements.
- Spatiotemporal scales need to be refined based on the geographic region. TAI responses to climatic conditions will differ (i.e., arctic and permafrost areas versus tropical).
- Need to determine what the models should study. Global vs regional? If global modeling is the goal, then need to study the change in wetland extent—where is it now and where is it changing?

Summary of Workshop Discussion – Measurement Gaps at TAI

- It is likely that the hydrodynamics of TAIs are the basis of modeling efforts. Although difficult to measure, there is a need to include lateral transport of material and energy as a key process at TAI.
- Steep geochemical gradients and compressed spatial scales are fundamental features of TAI and impact its processes.
- The goals of the modeling effort will determine what types of TAI sites need high-resolution measurements and their priority. Sites that are dominated by key processes? Sites that are changing rapidly due to human impacts (urbanization, land use, water and sediment diversion)? Sites that are changing rapidly due to climate change (permafrost thaw, hurricane frequency, landslides)? Or, “generic” coastal TAI sites?
- Research at the TAI requires new sensor and measurement technology, including the following:

- Geolocalization—elevation and elevation change in TAIs are currently a serious limitation. Can a collaboration with the NOAA Sentinel Site network of elevation-controlled TAI sites be leveraged?
- Non-destructive below ground measurements that provide information on microbial and geochemical processes are needed. How can we model these processes instead? Is there a way it can be studied nondestructively (for example, through microbial communities and redox boundaries)?
- Sensors are needed for capturing particulate matter flux.

6.0 Elevation is Key to Understanding a Wetland's Carbon Budget

Presentation by Adam Langley

Summary of Presentation

Elevation is key to understanding a wetland's carbon budget

For low lying coastal wetlands, no variable is more important to map and model than elevation. Where the system is perched in the tidal frame is an important indicator of biogeochemical activity, carbon sequestration, ecosystem services, and storm protection. Knowing how the elevation is changing affords a good estimate of the wetland's carbon balance and allows predictions for the fate of that ecosystem through elevation models.

Sedimentation/soil/surface elevation tables (SETs) provides a collaborative starting point for measuring elevation change and variability in wetlands, particularly in response to experimental manipulations[12]. See figure 6.1.

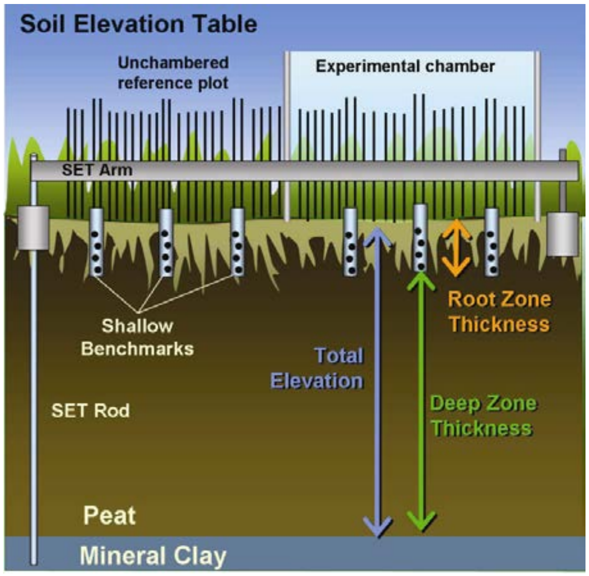

Figure 6.1. System for elevation measurement in experimental plots. Langley et al. 2009.

Elevation influences functional plant types

Aside from perhaps changes in sediment load, one of the most dominant drivers of elevation change is altered vegetation. Tom Mozdzer at Bryn Mawr College used SET to study the migration of phragmites, a type of large perennial wetland grass found in SERC. They found that phragmites migration increased elevation. Similarly, Coldren et al. 2018[13] found that mangrove migration under warming conditions increased elevation. Not only does this create variability in suspended sediments, but it also influences plant functional types. The type of plants able to grow in this area is important because few plants can tolerate the combination of salinity and flooding stressors that exist in coastal wetlands. Ecological niches develop as a result. Currently there are only three functional plant types represented. Elevation can be more influential to wetland processes than the effects of carbon dioxide, nitrogen, and phosphorus, though elevation effects may be specific to salt marshes. Findings from elevation experiments suggest the processes driving long-term carbon stabilization in wetlands is very different from upland ecosystems, but the mechanisms are unclear.

Elevation monitoring can be used to validate models, but experiments are needed to build models

Experimentation is essential to developing and validating models particularly in TAIs where multiple drivers interact to control ecosystem processes. Tradeoffs between precision and realism inform experimental design such that the optimal scale and treatments will vary with the particular question.

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[12] Langley, J.A., Sigrist, M.V., Duls, J., Cahoon, D.R., Lynch, J.C., Megonigal, J.P. (2009). Global change and marsh elevation dynamics: experimenting where land meets sea and biology meets geology. In: Lang, M.A. (ed) *Smithsonian Marine Science Symposium. Smithsonian Contributions to the Marine Sciences*, 38.

[13] Coldren, G.A., Langley, J.A., Feller, I.C., Chapman, S.K. (2018). Warming accelerates mangrove expansion and surface elevation gain in a subtropical wetland. *Journal of Ecology* 107(1):79-90. doi:10.5061/dryad.7b150n7.

Smaller-scale experiments offer higher precision in treatment application and assessment of response variables, while larger-scale experiments offer greater realism. TAI biogeochemistry is complicated by fluctuations in factors such as redox status and salinity, which strongly control microbial processes. We lack an adequate mechanistic understanding of how these factors interact in realistic systems. Biogeochemical models are introducing these factors because they are fundamental to TAI functioning. These models have been tested in laboratory microcosms (e.g. Tang et al. 2016[14]) that allow for precise control of experimental variables and precise measurement. Yet, results from small-scale experiments do not always translate to actual ecosystems. For instance, thousands of soil incubations have shown dominant effects of temperature on soil respiration. Yet, an extreme experimental warming of deep peatland soil *in situ* yielded no stimulation of soil respiration (Wilson et al. 2016[15]).

We must manipulate proximal drivers

Field experiments can apply realistic treatments (e.g., elevated CO_2, warming, salinization, flooding) and examine how ecosystem processes respond. While it is a great advantage to be able to attribute responses to one global change driver, some experimental treatments, such as warming or flooding, confound proximal drivers, such as soil moisture, salinity, pH, and redox status, that are known to have profound control over ecosystem processes and mediate the influence of global change drivers. For instance, an ecosystem warming study will alter temperature, but also soil moisture and potentially salinity. Similarly, a flooding manipulation (such as Langley et al. 2013[16]) will simultaneously alter redox status, soil moisture, and salinity. Biogeochemical models handle these variables individually. Therefore, especially in TAIs, we need field experiments capable of isolating the effects of proximal drivers to allow for the development and validation of models.

End of Day Reflections

Key gap at the TAI includes:

- High-resolution elevation maps of coastal ecosystems.
- Geographically distributed understanding of how elevation is changing
- The key biological drivers of elevation change

To close this gap, we need:

- Distributed network of elevation measurements.
- Experimental manipulations of key drivers of change in which elevation change is assessed.
- Coupling of elevation models and experimental data.

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[14] Tang, G., Zheng, J., Xu, X., Yang, Z., Graham, D.E., Gu, B., Thornton, P.E. (2016). Biogeochemical modeling of CO 2 and CH 4 production in anoxic Arctic soil microcosms. *Biogeosciences*, *13*(17), 5021-5041.

[15] Wilson, R.M., Hopple, A.M., Tfaily, M.M., Sebestyen, S.D., Schadt, C.W., Pfeifer-Meister, L., Kolka, R.K. (2016). Stability of peatland carbon to rising temperatures. *Nature communications*, *7*, 13723.

[16] Langley, J. Adam, Mozdzer, T. J., Shepard, K. A., Hagerty, S. B., & Patrick Megonigal, J. (2013). Tidal marsh plant responses to elevated CO2, nitrogen fertilization, and sea level rise. *Global change biology*, *19*(5), 1495-1503.

7.0 Disturbance and Extreme Events at TAI

Presentation by Neil Ganju

Summary of Presentation

Managed large tidal rivers can artificially manipulate sediment fluxes

Research in the Amazon River Basin demonstrates the difficult of estimating sediment budgets in large tidal river systems because significant amounts of sediment are trapped where smaller tributaries intersect (Fricke et al. 2017).[17] The timescales of these trappings are unknown. In the Mekong River, high flow regime exports mud, though sand remains upland. During low flow regime, sediment is imported with depositional signatures dependent on bathymetry. This creates complicated trapping dynamics and bed textures, with trappings in distributary channels (Nowacki et al. 2015[18]; Ogston et al. 2017[19]). In the Hudson River, interannual storage of sediment within shoals complicates export signals during spring. In the San Francisco Bay, a watershed sediment pulse from the 1880s moved through the system over several decades. A late 1990s flood year washed out the 150-year-old fine sediment accumulation in the delta. These pulses have ramifications for wetland restoration, fish habitat quality, and contaminant dynamics (Schoellhamer 2011[20]). Trapping rates, roles of dredging, external supply, and change in size and position are largely unknown. Responses to pulses are variable and dependent on flow and supply. Is there a way to connect residence time and material transport at this scale? This is a potential area of research to tie in flux balance.

Winds responsible for most erosion and control the direction

Results suggest open coast and estuaries respond to storm wind direction (Ganju et al. 2017[21]; Nowacki et al. 2017[22]). Subtle differences in morphology and flow patterns may govern net sediment transport. When the maximum erosion rate is normalized to maximum wave height, data shows the biggest storms are not responsible for the greatest erosion rates. Storms cause deposition of materials from mudflats, marsh edges, and overwash (Walters and Kirwan 2016[23]).

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[17] Fricke, et al. (2017). River tributaries as sediment sinks: processes operating where the Tapajos and Xingu rivers meet the Amazon tidal river. *Sedimentology*, Vol 64, Issue 6. doi:10.1111/sed.12372.

[18] Nowacki, et al. (2015). Sediment dynamics in the lower Mekong River: transition from tidal river to estuary. *Journal of Geophysical Research: Oceans*. doi:10.1002/2015JC010754.

[19] Ogston, et al. (2017). Building a tropical delta yesterday, today and tomorrow: the Mekong System. *Oceanography*. 30(3):10-21. doi:10.5670/oceanog.2017.310.

[20] Gregory G. Shellenbarger and David H. Schoellhamer (2011). Continuous Salinity and Temperature Data from San Francisco Estuary, 1982–2002: Trends and the Salinity–Freshwater Inflow Relationship. *Journal of Coastal Research*: Volume 27, Issue 6: pp. 1191 – 1201. doi: 10.2112/JCOASTRES-D-10-00113.1.

[21] Ganju, et al. (2017). Physical response of a back-barrier estuary to a post-tropical cyclone. Journal of Geophysical Research: Oceans. doi:10.1002/2016JC012344.

[22] Nowacki, D.J., Beudin, A., Ganju, N.K. (2017). Spectral wave dissipation by submerged aquatic vegetation in a back-barrier estuary. *Limn. Ocean*, 62, 736-753.

[23] Walters, D.C. and Kirwan, M.L. (2016). Optimal hurricane overwash thickness for maximizing marsh resilience to sea level rise. *Ecology and evolution*, 6(9), 2948-2956.

The ratio between the unvegetated and vegetated marsh can be used as an independent measure of stability

Sediment budget predictions can be made based on this ratio, as loss of vegetation increases the liberation of sediments. A healthy marsh should have minimal ponding from root collapse. This ratio ties sea-level rise, sediment budget, and marsh processes together. The stability value is approximately 0.9. In terms of scaling, particulate organic carbon flux can be used as a function, in remote sensing, of unvegetated/vegetated ratio. A good relationship exists between elevation and the unvegetated/vegetated ratio, so it can be inferred that particulate organic carbon flux is related to elevation. There is also a relationship between particulate organic carbon flux into tidal channels and particulate organic carbon flux from lateral erosion.

It is unknown if carbon release from the pulse event matters over the long-term

Natural marshes store carbon through uptake and burial. Drained marshes release carbon. Restricted marshes release increased amounts of methane due to salinity reduction. Significant methane release could be mitigated by restoring tidal flow to restricted wetlands (Kroeger et al. 2017[24]). Time scales of integrative metrics are critical to address whole-system response. In situ measurements, remotely-sensed data, and numerical models are necessary. 3D-geomorphic continuum should be considered, though uncertainties exist at small scales. Board-scale conceptual models of systems is useful to fill in gaps.

Another indicator of change can be tidal-creek geomorphology (dendritic patterns of tidal creeks)

Treat vegetation as a geomorphic feature, not an organism. In non-eroding marshes, primary production is higher than the burial, so there is export from non-eroding marshes. Open water marshes have higher respiration rates that can be generated by primary production. Geomorphology could be a good indicator of wetland loss.

Summary of Breakout Group Discussions

Group A - What features/characteristics of disturbance/extreme events are most important at the TAI that would inform ESMs? Which are not being adequately measured?

- Need better sensors for continuous measurements of flux
- Incorporate microbial community structure into representations of the ecosystem state and as indicators of change
- Changes in redox potential, or the presence of microbial functional groups such as nitrifiers to indicate low oxygen, sulfate reducers to indicate rates of organic matter mineralization, and methanogens and methanotrophs to indicate the potential for methane emissions
- Differential gradients may be a solution to understanding environmental changes
- Changes in organic matter molecular composition over time
- Changes in plant community structure and productivity
- Changes in trophic levels and grazing that affect the system.

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

Group B - What spatial/temporal scales are most relevant for measurement of disturbances and extreme events?

- Characteristics to measure:
  - Hydrodynamics
  - Plant community composition
  - Soil characteristics and elevation
  - Vertical and lateral fluxes in carbon, nutrients, and sediment transport; need to find the first order drivers of these fluxes
  - Scaling across gradients of space and time; 30-meter landsat-based spatial scale would be a good start, then downscale to capture finer resolution
- Natural and anthropogenic disturbances and episodic events
- Disturbance across predictable temporal scales and unpredictable episodic scales
- Need to measure the time it takes to transition from disturbed to undisturbed state
- Understand network of materials exchange for metabolic scaling.

Group C - How are "hot spots and moments" best captured and modeled at TAI?

- As a process-based or statistical definition; statistical approach will have more relevance
- Hotspots should have more than 75% higher values than normal in space and moment in time
- What should be measured might be discipline-specific or driven by a process
- Need better ways to measure salinity remotely
- Top-down approach is best at identifying hot spots and moments.

8.0 Existing Regional and National Networks

Presentation by Chuck Hopkinson

Summary of Presentation

Network inputs from temporal watershed and ocean scenarios can be used as drivers for coastal system models, rather than local scale inputs

It is not enough to simply understand coastal system response to local climate change and sea-level rise—it is also important to know coastal system response to varying inputs and connections from land and the continental shelf/ocean. Systems adjacent to coastlines, such as shelf/ocean and adjacent terrestrial, dominate the internal dynamics of coastal zones. It is therefore critical to develop a research program that not only integrates this data with ESMs, but also enables a predictive understanding of change in estuaries and tidal wetlands.

Establishing coastal networks is important to ensure generality of results

Coastal networks are useful for further testing and development of models, helping to insure their generality and applicability elsewhere. Even the most complete knowledge base for a single system cannot provide a predictive understanding for all other coastal systems. There are several existing networks relevant to the land-sea and terrestrial–aquatic interface studies.

Four estuaries exist along the Atlantic Coast that are ideal research sites: Plum Island Ecosystems (Massachusetts), Virginia Coast Reserve (Virginia), Georgia Coastal Ecosystems (Georgia), and Florida Coastal Everglades (Florida). They are adjacent to different watersheds, with diverse population densities and discharge into waters with continental shelves located in four biogeographic provinces. These four sites are in different climatic zones, with varying temperature, precipitation, sediment supply, sea-level rise, and extreme events like ocean storms. Their driver effects appear to be freshwater inflow (quantity, and timing, as well as quality of water, sediment, and other materials), estuarine conditions (transit time, salinity, light levels, sedimentation, and nutrient enrichment), and estuarine resources (wetland extent and condition, habitat distribution, and primary and secondary production). The considerable variation between each driver from site to site makes it impossible to generalize land-sea interface systems based on a few site-specific studies. However, creating a network of coastal sites across various gradients, both inland and in estuaries, can help to inform coastal system models.

Continental scale data can create more accurate predictive models

At a continental scale, there are numerous programs currently performing coastal research (see Figure 8.1).[25] By pulling together data from these sites, including multi-scale remote sensing and spatiotemporal modeling, we gain a better understanding of the drivers at different gradients, and can create more accurate predictive models.

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[25] Hopkinson, et al. (2008). Forecasting effects of sea-level rise and windstorms on coastal and inland ecosystems. *Front Ecol Environ*, 6(5): 255-263. doi:10.1890/070153.

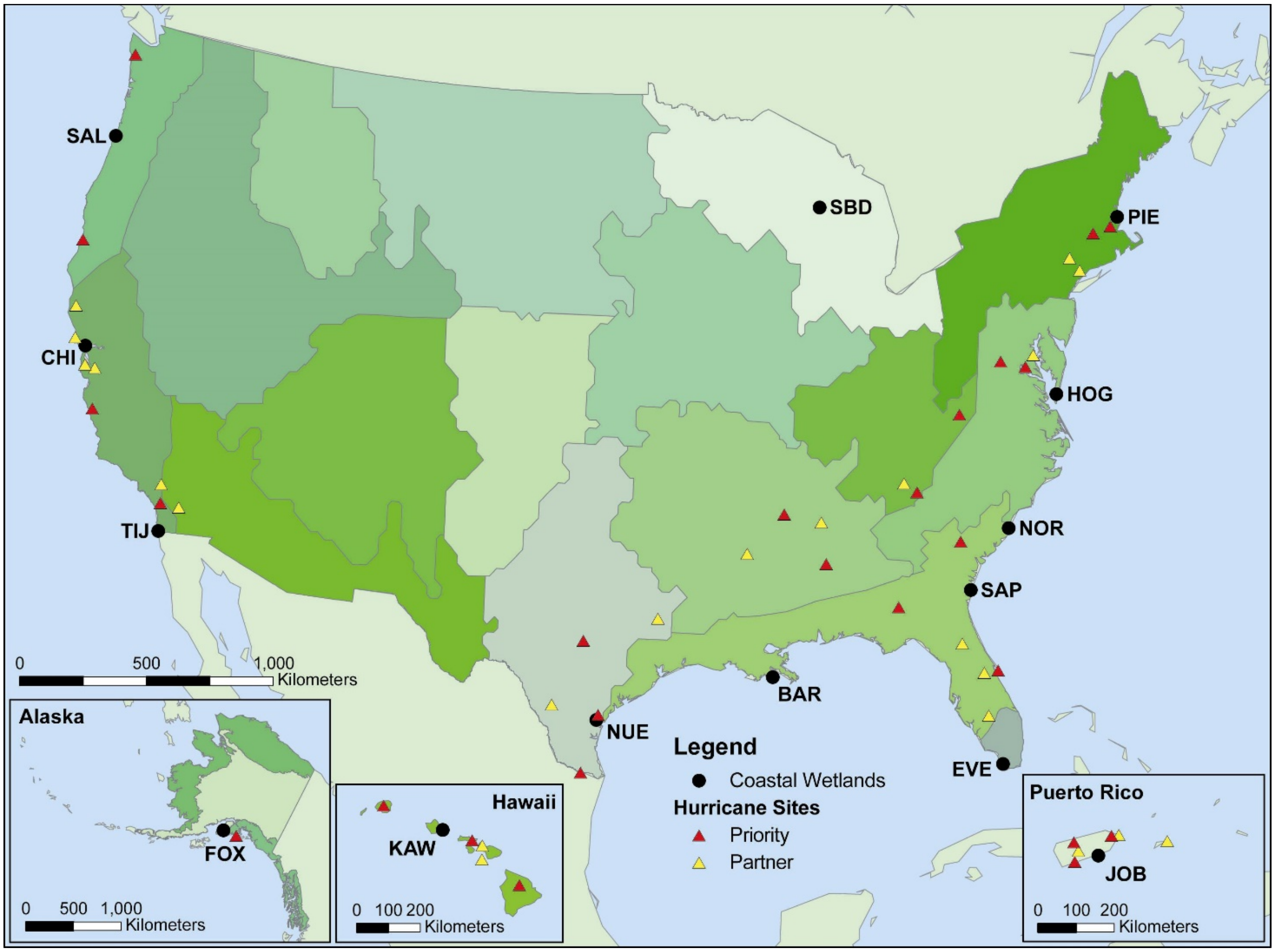

Figure 8.1. Coastal research sites run by various agencies and programs. Courtesy Chuck Hopkinson, modified from Hopkinson et al. 2008.

To facilitate this large-scale data collection, a call out needs to be made to a huge number of partners

Operating long-term experimental sites will require greater participation from local and regional research groups, such as academic institutions and government agencies. There needs to be a rationale for the inclusion of sites in a coastal network by creating site tiers, such as monitoring sites to capture status and trends, experimental sites to understand mechanistic controls' model development sites to calibrate models incorporating mechanistic control experiments, and model validation sites where the generality of model results are examined.

Summary of Breakout Group Discussion

Group A - How can we best leverage existing TAI sites and networks?

- Be strategic in using existing sites and create a network of simultaneous measurements on land and in ocean.
- Synthesize existing data. The depositional environment is critical to understanding the two-way relationship.

- Make a matrix of existing sites and assess whether these sites have legitimate transects. Look at east, west, and gulf coasts in the context of the scaling graph. Once the transects are identified they could be used to synthesize existing data, target building communities of practice along and between each transect, generate fine-scale modeling of upland-to-coastal fluxes, and coordinate experimentation with the same design.

Group B - What criteria can be used to identify new TAI study sites to fill data gaps?

- Criteria for new TAI study sites:
  - Geography—climate, land use, population, and human impacts
  - Geological areas (karst, volcanic, sedimentary)
  - Geomorphology and near-shore characteristics (shallow, deep, fetch, bathymetry)
  - Relative magnitude and rate of sea-level rise
  - Hydrodynamics, tidal range, steepness of gradient
  - Disturbance regimes
  - Transpiration potential
  - Vegetation types, invasion, and mortality
  - Biogeochemistry and salinity
  - Contaminants
  - Extension of existing sites to see if additional sensors can be added
  - Existing NASA satellite imagery to monitor water level.
- Data gaps:
  - Biogeochemical cycling—microbial processes and mechanisms, as well as carbon sequestration and accumulation in TAIs
  - Fate of organic matter and lateral flux of carbon transport in TAIs
  - Vegetation feedbacks and response to flooding
  - Plant-microbe feedbacks.

Group C - What is the ideal combination of "core" observations made across a large number of sites and resource-demanding or unique observations made at a subset of sites in order to enrich process understanding?

- Need a combination of stationary sensor-based measurements for temporal and remote sensing, and physical measurements taken by people in the field
- Use NEON frameworks
- Develop a measurement plan by physical domain—water/hydrodynamics, structure/geomorphology, biogeochemical, terrestrial surface and soils, and atmosphere
- Core process measurements needed—terrestrial primary production/respiration, aquatic metabolism of CO_2 and O_2, and dissolved inorganic carbon and dissolved organic carbon
- Networked targeted sampling approach
  - Event driven

- Pore water/chemistry
- Calibrations and system differentiation
- REDOX
- Organic matter quality
- Microbial species composition and metagenomics data
- Bacterial production.

9.0 Key Take-Aways

Perhaps the most common, overarching question that emerged from the workshop regarded understanding what factors and mechanisms lead to resistance and resilience, or lack thereof, in TAI ecosystems in response to external drivers, including both press and pulse disturbances. Environmental drivers that are recognized as key drivers include rising temperature, increased frequency of drought, and increased frequency of storm surges. Knowledge that is required to more fully assess resistance and resilience includes the following:

- Identifying TAI boundaries
- Measuring and modeling changes in TAI boundaries due to external drivers
- Measuring and modeling the two-way exchanges of carbon, water, energy, nutrients, and sediments across TAI boundaries
- Measuring and modeling the transformations of carbon and nutrients within TAI boundaries
- Understanding the roles of plants and microbes in forming the TAI boundaries and regulating the fluxes and transformations of mass and energy within and across the boundaries.

Modeling challenges are significant, as simulations of coastal TAI's have not been previously attempted in ESMs. To improve ESM representation of TAI's, we require the following:

- Determination as to whether using E3SM, with development, is more effective than using an entirely new model built from scratch
- A MODEX approach to testing the overarching questions; improved knowledge of fluxes of carbon, water, nutrients, and sediment, and the role of microbial and plant populations
- Development at intensively monitored sites, and evaluation at distributed, less intensively measured sites
- Future models integrate hydrology, biogeochemistry, vegetation ecology and physiology, sedimentology, and responses to disturbances.

The commonly agreed upon experimental design included a hierarchy of measurement intensity, with a few sites intensively measured and many distributed sites less intensively measured.

- Model development will occur at intensively measured sites
- Model evaluation will occur at distributed sites
- To understand cause-and-effect for proper system modeling, manipulative experiments that uncover mechanisms regulating vegetation and microbial responses to changes in drivers are required
- The transdisciplinary nature of TAI research requires understanding carbon, nutrients, water, and sediments, but carbon provides a universal currency due to its linkages to the storage and transport of the other key variables.

Appendix A

Agenda

STAR Workshop: Terrestrial Aquatic Interfaces
Discovery Hall, 650 Horn Rapids Road, Richland, WA
Horizon D & E

Pacific Northwest
NATIONAL LABORATORY

AGENDA September 24-26, 2018

STAR
System for Terrestrial-Aquatic Research

Monday Sept 24 (PNNL Discovery Hall)

7:15 – 7:30: Meet in lobby and board A&A Motorcoach bus

- 7:30 am: Bus Departs Hilton Homewood Suites for PNNL

7:45 – 8:15: Networking and refreshments

8:15 – 8:45: **Introductions and Overview of the Workshop** (Nick Ward and Pat Megonigal)

8:45 – 9:15: **Importance of TAI from Ecological and Functional Perspective** (Vanessa Bailey)

9:15 – 9:45: **Coastal TAI from Modeling Perspective** (Peter Thornton)
Possible Scope: Could cover various classes of models that presently address TAI processes (e.g. marsh elevation models, geomorphic models, hydrologic models). May reflect on the extent to which ESMs include key TAI processes, and potential to couple existing models.

9:45 – 10:00 Break

10:00 – 12:00 Group discussion about gaps in models, starting with ESMs, followed by regional/local scale. How do we bring together modeling communities and products from the many communities working on the TAI in terrestrial, wetland, hydrologic, riverine, estuarine and marine systems?

12:00 - 1:00: Working Lunch – Q&A for group discussion

1:00 – 1:30: **Measurement Gaps Relevant to Modeling** (Lisamarie Windham-Myers)
Possible Scope: Scaling across space and time in support of models requires spatial data and temporal data that might be provided through combinations of remote sensing, sensor networks, intensive study site networks.

- What technologies have proven most insightful for informing and parameterizing models?
- Which technologies are currently under-utilized?
- How much can be done with sensors/automated systems vs man-power?
- What suites of measurements are most powerful for linking across scales?

1:30 – 2:30 Group discussion

2:30 – 2:45 Break

3:00-3:30: **Experimental Approaches for Model Parameterization** (Adam Langley)
Possible Scope: The scope of the models can be as broad as you wish, ranging from parsimonious marsh elevation models, to process-rich models such as DNDC, and hydrologic or spatial models that you may be familiar with. Insights on integating experiments, spatially limited detailed observations, and spatially extensive but less detailed observations would be useful.

- What are key processes that are poorly quantified from a modeling perspective?
- What measurements are needed to reduce model uncertainty?

3:30 - 4:45: Group discussion

4:45 - 5:00: Wrap up and Reflection on the day's presentations and discussion (Pat Megonigal)

5:00: Depart for dinner at Anthony's Restaurant (A&A Motorcoach bus provided). Bus will return visitors to the Hilton Homewood Suites following dinner.

Tuesday Sept 25 (PNNL Discovery Hall) – Break out groups working towards an opinion paper

7:15 – 7:30: Meet in lobby and board A&A Motorcoach bus
- 7:30 am: Bus Departs Hilton Homewood Suites for PNNL

7:45 – 8:15 Networking and refreshments

8:15 – 8:30 Introduction for today's plan (Nick Ward)

8:30 – 9:00 **Disturbance and extreme events at TAI** (Neil Ganju)
Possible Scope: May cover both press and pulse disturbances to vegetation, geomorphic processes, and hydrologic processes, likely causing ecosystem degradation or state change. Insights on the extent to which underlying processes are understood, or how processes can be scaled would be helpful.

9:00 – 10:30 Breakout Groups on **Disturbances/Extreme Events**
- A: What features/characteristics of disturbance/extreme events are most important at the TAI that would inform ESM? Which are not being adequately measured? (Liz Canuel)
- B: What spatial/temporal scales are most relevant for measurement of disturbances and extreme events? (Chris Osburn)
- C: How are "hot spots and moments" best captured and modeled at TAI? (Rodrigo Vargas)

10:30 – 10:45 Break

10:45 – 12:00 Groups report on their discussions

12:00 – 1:00 Working Lunch – reach consensus on unresolved topics

1:00 – 1:45 **Existing Regional and National Networks** (Chuck Hopkinson)
Possible Scope: The variety of formal and informal networks presently collecting data relevant to coastal TAI processes. The extent to which the networks share data and the potential for additional integration. Insights on gaps that might be filled by new efforts would be helpful.

1:45 – 3:30 Breakout Groups on **Experimental Approaches** and **Leveraging Existing Networks**
- A: How can we best leverage existing TAI sites and networks? (Heida Diefenderfer)
- B: What criteria can be used to identify new TAI study sites to fill data gaps? (René Price)

- C: What is the ideal combination of "core" observations made across a large number of sites and resource-demanding or unique observations made a subset of sites in order to enrich process understanding? (David Butman)

3:30 – 3:45 Break

3:45 – 4:45 Groups report on their discussions and reach consensus on unresolved topics

4:45 – 5:00 Wrap-up discussion and preview of what needs to get done tomorrow (Pat Megonigal)

5:00 – A&A Motorcoach bus will return all to the Hilton Homewood Suites. You may either eat at the hotel (no charge, light meal, includes wine) or walk to Fat Olive's

5:30 – If electing to eat dinner at Fat Olive's Restaurant walk to: 255 Williams Blvd, Richland

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Wednesday Sept 26 (PNNL Discovery Hall)

7:30 – 7:45: Meet in lobby and board A&A Motorcoach bus
- 7:45 am: Bus Departs Hilton Homewood Suites for PNNL – There is ample room to bring your belongings with you (and space at Discovery Hall to store)

8:00 - 8:15 Networking and refreshments

8:15 – 8:30 Introduction for today's plan (Nick Ward)

8:30 – 10:30 Writing Groups - findings of workshop and identify omissions
- **Importance of coastal TAIs from ecological and functional perspective**
    - Ecosystem scale interactions between soils, vegetation, and water
    - Molecular level TAI interactions and cycles
    - Measuring and modeling "hot spots and hot moments"
- **TAI representation in Earth System Models**
    - Current state of the art
    - Measurement gaps for current models
        - Leveraging existing monitoring networks
        - Optimal features and distribution of new TAI research sites
    - Experimental approaches for model parameterization
- **Disturbance and extreme events at TAIs**
    - Contrasting effects of press and pulse disturbance
    - Spatiotemporal scales relevant for study of disturbances and extreme events
    - Impactful features of disturbances most important to represent in ESMs

10:30 – 10:45 Break

10:45 – 12:15 Conclusions, final matters to address (Nick Ward, Pat Megonigal)

12:15 - Adjourn (box lunches provided) – A&A Motorcoach bus will return visitors to the Homewood Suites (if needed) and will continue on to the Pasco airport.

STAR Workshop: Terrestrial Aquatic Interfaces
Discovery Hall, 650 Horn Rapids Road, Richland, WA
Horizon D & E

Attendees

Nick Ward (PNNL) – Co-Chair	James T. Morris (USC)
Pat Megonigal (SERC) – Co-Chair	Rebecca Neumann (UW)
Lihini Aluwihare (UCSD)	Chris Osburn (NCSU)
Gautum Bisht (LBNL)	René M. Price (FIU)
David Butman (UW)	Joel Rowland (LANL)
Elizabeth Canuel (VIMS)	Marc Simard (NASA)
Emmett Duffy (SERC)	Peter Thornton (ORNL)
Neil Kamal Ganju (USGS)	Robert Twilley (LSU)
Miguel Goni (OregonState)	Maria Tzortziou (CUNY)
Chuck Hopkinson (UGa)	Jesse Vance (NEON)
Jay Jones (UAlaska)	Rodrigo Vargas (U of Delaware)
Adam Langley (Villanova)	Pamela Weisenhorn (ANL)
Roser Matamala (ANL)	Lisamarie Windham-Myers (USGS)
Vanessa Bailey (PNNL)	Charlette Geffen (PNNL)
Heida Diefenderfer (PNNL)	Nancy Hess (PNNL)
Yilin Fang (PNNL)	Tarang Khangaonkar (PNNL)
Josh Shiode (PNNL)	Nate McDowell (PNNL)
Emily Graham (PNNL)	Aditi Sengupta (PNNL)

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