Project title: EESLR 2019 Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands

Institutions: Oregon State University, Pacific Northwest National Laboratories, University of Oregon, Institute for Applied Ecology

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Summary: Coastal wetlands such as tidal marshes and forested swamps provide a range of protective and non-protective ecosystem services to coastal communities throughout the United States such as flood control, carbon sequestration, and fisheries benefits. However, changing inundation and salinity due to sea-level rise (SLR) may impact the ecosystem services that tidal wetlands provide over the coming decades. Natural and nature-based features (NNBF) such as restored wetlands can be valuable management tools to maintain or enhance coastal services, especially in light of changing ocean and coastal watershed conditions. This project addresses the provision of coastal protection and blue carbon services of least-disturbed and restored tidal marshes and forested swamps in the Pacific Northwest (PNW) under a range of future restoration and SLR scenarios. Using local expertise among members of the project team and regional end-users, several future restoration and SLR scenarios in two representative estuaries will be developed. The study estuaries are on the outer coast of the PNW (Coos Estuary) and on the lower Columbia River (Grays Bay). Across the restoration scenarios and a range of SLR scenarios considered, the investigators will apply hydrodynamic models to assess how restored and natural coastal wetlands buffer flooding impacts during high water events. These restored and natural sites will also be evaluated for future changes in elevation using an ecosystem model of wetland change (WARMER). Using existing datasets and additional field data, researchers will assess changes in greenhouse gas (GHG) and carbon sequestration rates (blue carbon) in marshes and swamps along salinity, inundation, and land-use gradients. Finally, the data on coastal protection, blue carbon functioning, and future projections of wetland elevation will be synthesized into spatially explicit assessments of how coastal wetland services are expected to change in the future. The synthesis of outputs and potential outcomes— across a range of climate change and restoration scenarios—will help land managers, policy makers, scientists, and the public plan for coastal climate change and develop management actions that sustain ecosystem services into a changing future.

Topic addressed by the proposal

Tidal wetlands, including emergent marshes, scrub-shrub wetlands, and forested swamps, protect coastlines from damaging high-water events such as storm surge and coastal river flooding and provide an important suite of other ecosystem functions and services. These benefits include sediment stabilization and storage, nutrient removal, fish and wildlife habitat, flood water buffering and storage, and carbon sequestration (Mitch and Gosselink 2015). Given the range of benefits provided by tidal wetlands to coastal ecosystems and human communities, it is important to document current levels of services and predict how functions and services are likely to change with sea-level rise (SLR) and to proactively apply such findings to resilience management. In the U.S. Pacific Northwest (PNW) region (Fig. 1), geological processes have largely counter-balanced eustatic SLR rates in coastal areas since the last Cascadia Zone subduction earthquake in 1700. However, NOAA's coastal calculator and recent regional studies confirm that this trend is changing (Miller et al. 2018), with global SLR beginning to accelerate (Nerem et al. 2018). The impacts of SLR in the region are in addition to the substantial historical losses of PNW tidal wetlands through land-use changes, which already affect the provision of current and future wetland services (Borde et al. 2003a; Marcoe and Pilson 2017).

The ecological restoration of wetlands has the potential to counter trends of historic wetland loss and SLR vulnerability, restoring protective services that these ecosystems provide to coastal communities, especially flood mitigation (Thayer 1992). In fact, the most widespread type of managed Natural and Nature-based Features (NNBF) in the Pacific Northwest is tidal wetland restoration (Zedler 2001). This is most often accomplished by breaching levees historically built to exclude former tidal wetlands from hydrologic connection with their estuaries, and replacing the constructed networks of simplified ditches established to drain those tidal wetlands with restored tidal channel complexes. Managed NNBF have been implemented for over 20 years in the PNW to reduce wetland loss and to restore habitat for threatened and endangered juvenile salmon and trout (Rumrill and Cornu 1995; Simenstad and Thom 1996). Non-managed NNBF include least-disturbed tidal wetlands, that is, wetlands with structure and function suitable for reference status in comparison with restoration sites (Clewell and Aronson 2013), specifically, non-diked, relatively undisturbed marshes or tidal-swamps with unrestricted tidal–fluvial–wetland connectivity.

Numerous tidal wetland restoration programs implemented by federal, tribal, state, and other partners and stakeholders are currently working to restore wetlands in the outer coasts of Washington and Oregon, in the Salish Sea, and in the Columbia River Estuary. Although these activities are widely recognized for providing potential co-benefits to ecosystems and human communities such as the enhancement of coastal and fluvial fish stocks (Diefenderfer et al. 2016), investigation of potential carbon sequestration co-benefits is in the early stages (Crooks et al. 2014, Thorhaug et al. 2017). Tidal wetlands in the PNW are particularly poorly studied in almost all aspects relative to other areas of the U.S. The PIs on this proposal are involved in the first-ever comprehensive assessment of blue carbon soil stocks in PNW wetlands (including former tidal wetlands historically diked and converted to agricultural lands), the first-ever PNW blue carbon project feasibility assessments, and ongoing research on greenhouse gas fluxes from several PNW estuaries (Schultz et al. 2018).

The history of coastal communities in the PNW is unique in the continental U.S. in that there remain extensive rural areas with low population density and relatively high percentages of forest cover with the development of only a few large urban areas. Moreover, Northwest Indian Tribes have reservations and communities located along the coast and river floodplains and are very actively involved in driving coastal wetland restoration focused on habitat functions for fisheries resources such as juvenile salmon, eulachon, and lamprey.

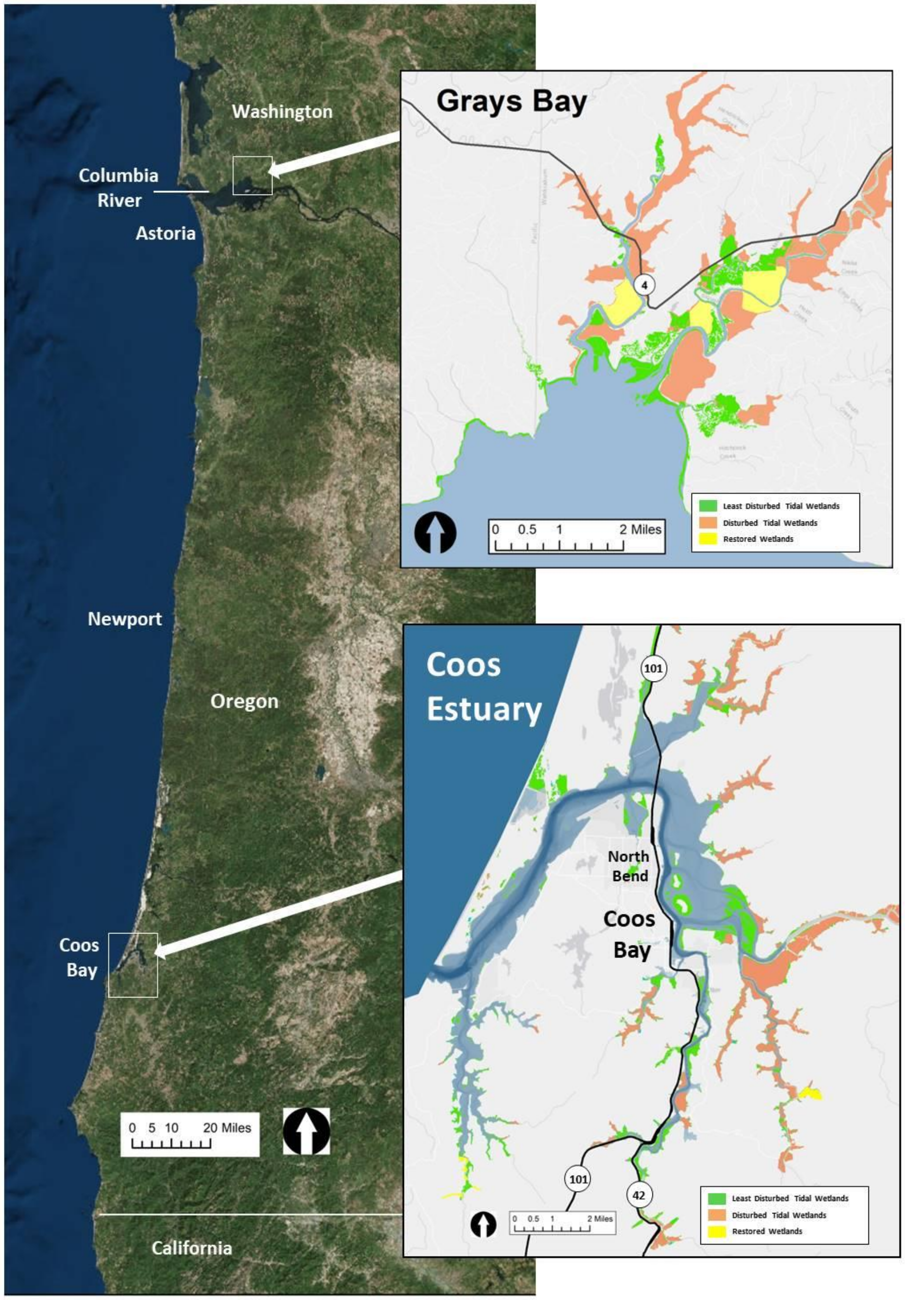

Fig. 1. Location of study areas (Coos Estuary and Grays Bay) in the Pacific Northwest.

Settlers in the 1800s built dikes to prevent tidal flooding, converting forestland, shrub-scrub, and marsh to dairy farms and cropland (Martin 1997). To date in the U.S., low-population rural areas such as these have not received the same level of attention as large urban areas that may be affected by SLR and hurricane-caused flooding. Our proposal aims to help address this gap. For example, transportation corridors located in low-lying areas along rivers and coasts are vital to PNW coastal communities, but are particularly vulnerable during storm events which frequently cause dangerous flooding in conjunction with power outages because of treefall on wires along forested roadsides (Fig. 2).

Fig. 2. The historic Grays River covered bridge and Rosburg-area roads near Highway 4 in Wahkiakum County, Washington, in the proposed Grays Bay study area. The bridge was constructed 1905-1908 and restored through local efforts in 1988 and is managed by the Grays River Grange. The combination of high tides and heavy precipitation leads to frequent flooding of Pacific Northwest coastal communities and major transportation corridors like this one in 2006, especially during the fall and winter months. *(Photos courtesy of Ian Sinks, Columbia Land Trust, Vancouver, WA).*

Despite the extensive and increasing efforts to use NNBF to protect coastal infrastructure and enhance coastal ecosystem services in the Pacific Northwest, partners and stakeholders are concerned about the lack of information regarding the degree to which wetlands will provide protective and non-protective services to coastal communities as they change over time in response to SLR; many have expressed enthusiastic support for the proposed research (see Attachment: Letters of Support). This concern has been described in multiple regional workshops convened in recent years at which we have presented research, with themes such as "Promoting Resiliency Under Shifting Environmental Conditions" at the 2018 Columbia River Estuary Conference in Astoria, OR. Coastal-zone and wetland managers, policy makers, and scientists in the region need more information on the vulnerability of restored and least-disturbed wetlands to SLR, the effects of changing inundation and salinity regimes on the services provided by these ecosystems under a range of future scenarios, and sources of uncertainty in projections about these impacts. For example, both federal and state agencies that provide funds for PNW coastal wetland projects (projects historically driven mainly for restoring salmon populations) are concerned that their investments will be long lasting. Therefore, resiliency of projects selected for funding is a high priority, with information needed on the resiliency of project designs to anticipated SLR-related changes. Likewise, because the concept of longevity is central to blue carbon financing, blue carbon project developers and investors need more information on long-term wetland resilience to evaluate the long term viability of carbon offset values.

Anticipated SLR impacts to estuaries are closely tied to existing wetland elevation, with sites that are higher in the tidal frame having more "elevation capital" than naturally-occurring low elevation sites, or restoration sites that have low elevation due to a history of diking and subsequent land subsidence prior to reconnection for restoration purposes (Cole Ekberg et al. 2017, Diefenderfer et al. 2008). Additionally, differences in vegetation composition along tidal and salinity gradients may impact sediment building processes through hydrological controls on plant species productivity (Janousek et al. 2016). From a management perspective, the most frequently raised question we have heard is, "at what elevation should we build a restoration site" (cf. Cornu and Sadro, 2002). In practice, many restoration projects on the PNW coast have been designed to "hedge bets" against SLR (Doherty and Zedler 2015) by incorporating microtopographic features such as mounds constructed to support vegetation that naturally occurs higher in the tidal frame, such as woody shrubs and trees (Diefenderfer et al. 2018b). Yet major acquisition and restoration investments require more robust understanding of how SLR is likely to impact the longer-term sustainability and function of new projects.

Uncertainties in modeling wetland responses to SLR arise because small to modest rates of SLR could facilitate increases in plant production (Alizad et al. 2016) and elevation gain in coastal wetlands (Morris et al. 2012), but higher rates could drown existing wetlands (Thorne et al. 2018), lead to increases in salinity that reduce plant productivity (Janousek et al., in prep), or alter GHG fluxes (Diefenderfer et al. 2018a, Poffenbarger et al. 2011). Coastal wetland plant communities are sensitive to salt concentrations and are arrayed along elevation gradients because of strong control by inundation, but both salinity intrusion and inundation dynamics change with SLR (Janousek et al. 2016; Borde et al. in review). Increasing water-table levels may increase methane (CH_4) emissions, whereas increasing salinity decreases CH_4 emissions (Poffenbarger et al. 2011). Thus, more information is needed on how important wetland functions (productivity, decomposition, greenhouse gas emissions, accretion) vary along the key gradients that will be affected by SLR. Finally, in comparison with marshes, the unique forested and other woody coastal wetland plant communities in the PNW are expected to have different responses to SLR and to provide substantially different protections, but quantitative data from these unique ecosystems are lacking relative to East and Gulf Coast ecosystems.

Proposed objectives and research activities

Our research objective is to evaluate how protective and non-protective ecosystem services of NNBF sites in the PNW (least-disturbed and restored wetlands) respond to sea-level rise and estuary-wide restoration scenarios. Specifically, we will examine how key wetland features such as elevation and vegetation composition affect the coastal protection conferred by coastal wetlands, quantify non-protective blue carbon sequestration services under alternative SLR and restoration conditions, and inform decision-makers regarding the impacts of NNBF on the provision of these services. Specifically, we will address two research questions:

(1) How does coastal protection provided by tidal marshes and forested wetlands change through ecosystem feedbacks under a range of SLR and estuary-wide restoration scenarios projected into the future? **[EESLR priority 1]** *We hypothesize that protective services during high water events are positively associated with restoration age, wetland elevation, habitat area, and vegetation succession.*

(2) How does the net balance between carbon sequestration and GHG emissions change with SLR scenarios and wetland elevation gain occurring during succession of restoration site? **[EESLR priority 3]** *We hypothesize that carbon sequestration declines with time since restoration while GHG emissions increase with establishment of vascular plants and decline with salinization.*

To address these questions, we propose to integrate coastal hydrodynamic modeling (FVCOM) with a tidal wetland elevation model (WARMER), a statistical model of GHG emissions, and a conceptual model of geomorphic evolution and plant community assembly in PNW estuaries in two large, representative study areas: Grays Bay, WA (on the lower Columbia River Estuary) and the Coos Estuary on the outer coast of southern Oregon (Fig. 3). We will evaluate outputs of these models across several combinations of SLR-by-restoration scenarios to assess how protective and blue carbon services change across a range of potential future conditions. We will collaborate with the primary supporters of the research (Attachment: Letters of Support) during the project to ensure that the *outputs* of the project—hydrodynamic and ecosystem modeling outputs, synthesis in ArcGIS, fact sheets, regional end users' meeting, project report, and published peer-reviewed papers— have the greatest possible utility and benefits for policy and management *outcomes*.

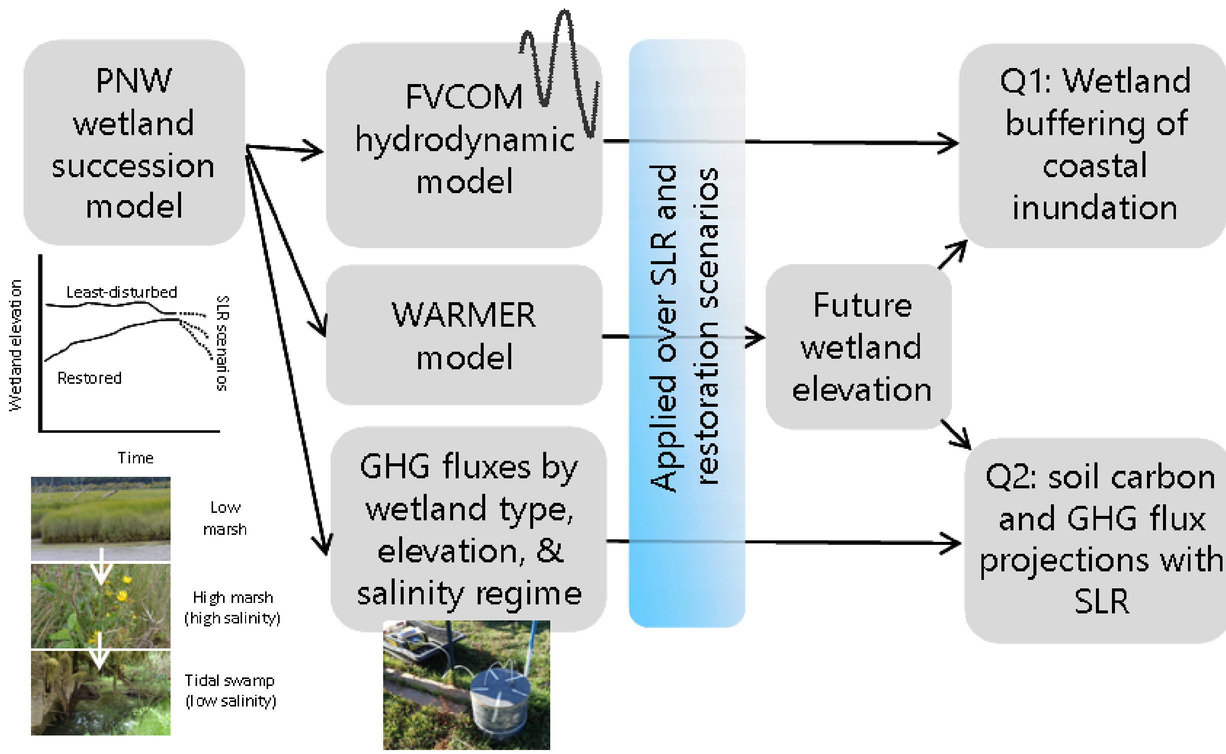

Figure 3. Conceptual model linking the major research objectives and tasks in this project. Hydrodynamic modeling (task 2), WARMER modeling of wetland elevation with sea-level rise (task 4), and soil carbon sequestration and GHG measurements across wetland types, and elevation and salinity gradients (task 3) are applied over different SLR and restoration scenarios developed in the project (task 1) to address how SLR will affect wetland buffering of high water events (research question 1), and blue carbon balance (research question 2) in two representative estuaries in the PNW.

To evaluate the protective and blue carbon services of tidal wetlands in the PNW under a range of restoration and SLR scenarios, we outline five tasks below that address our two research questions and help translate results into usable information and policy and management-decision outcomes for regional land managers and restoration practitioners.

Task 1: Develop spatially explicit NNBF (restoration) and SLR scenarios

We will develop multiple scenarios of wetland restoration and SLR for both estuarine study areas at the landscape scale (i.e., Fig. 1 insets) in ArcGIS in preparation for hydrodynamic and ecosystem modeling. Tidal wetland restoration of previously impounded wetlands is ongoing in the PNW, with recent large projects implemented in Tillamook Bay, Coquille River Estuary, Nisqually River Delta, and Salmon River Estuary. Extensive wetland restoration has occurred in both Coos Estuary and Grays Bay, with intensive post-restoration monitoring conducted by the PIs of this proposed study that will inform scenario development and interpretation of project results (e.g., Cornu 2005, Diefenderfer et al. 2016, Schultz et al. 2018). Tidal wetland restoration in the lower Columbia River including the Grays Bay study area is further described in letters of support from the U.S. Army Corps of Engineers Portland District, Columbia Land Trust, and Bonneville Power Administration; restoration on the outer Oregon Coast, including the Coos Estuary study area, is discussed in letters of support from South Slough National

Estuarine Research Reserve, the Coos Watershed Association, and the Oregon Department of Land Conservation and Development's Coastal Management Program (Attachment: Letters of Support). The state and federal entities and NGOs that have indicated strong support for this project regularly face a dearth of information to support necessary planning and engineering decisions in regard to NNBFs in the PNW.

Restoration of plant communities in PNW tidal wetland dike-breach/removal projects typically occurs by natural recruitment of tidally-borne plant propagules from nearby least-disturbed wetlands and vegetative spread of plants. Tidal wetland surface elevations, normally maintained relative to sea-level by sediment inputs and within-site plant inputs, can subside after decades behind dikes and by physical soil compaction associated with various land-use activities (Diefenderfer et al. 2008). Therefore, newly restored wetlands often begin as low-elevation, unvegetated tidal flats that develop successional plant communities over time as the wetland surface steadily accumulates sediments and organic material and rises higher in the tidal frame (Cornu and Sadro 2002).

A conceptual model of gradual wetland succession from low marsh to high marsh to tidal swamp (under low salinity conditions) and low marsh to high marsh (under higher salinity conditions) guides our approach to modeling and interpreting elevation change within restoration sites in the coming decades (Fig. 3). In high salinity areas, restored wetlands are anticipated to develop into high marshes dominated by halophytic graminoids and forbs; however in tidal fresh and oligohaline areas, tidal forests dominated by *Picea sitchensis* (Sitka spruce) may eventually become established. This habitat type is unique to the PNW, but is very poorly studied and has been particularly affected by historical land use changes that dramatically reduced Sitka spruce swamp area to a small fraction of its original extent (Marcoe and Pilson, 2017). In landscape ecology terminology, Sitka spruce forested wetland was the coastal "matrix" historically, within which other habitat types such as marshes also occurred. Both mature high marshes and Sitka spruce swamps offer opportunities for substantial carbon storage potential, coastline protection from flooding, and juvenile salmon support, but much more information is needed on change in these functions as wetlands mature and are affected by SLR. In lower elevation parts of the study areas, emergent marshes are tidal freshwater in Grays Bay (Borde et al. in review), and tidal freshwater, mesohaline, and polyhaline in Coos Estuary. Thus, comparison of the two estuaries also provides opportunities to consider the effects of SLR and changes in salinity regimes on both large and small coastal rivers, capturing some of the range of diversity of tidal wetlands in the PNW.

Grays Bay Study Area. Deep River and Grays River flow into Grays Bay along with the much smaller Secret River and Crooked Creek (Fig. 1). This study area has been the subject of an acquisition and restoration program for at least 15 years, led by the Columbia Land Trust (Vancouver, WA). In turn, this program has provided the basis for a body of recent ecohydrological research and modeling that will inform the proposed study. In particular, potential restoration scenarios have been examined in a hydrodynamic modeling effort to estimate the resulting flooded area (Coleman et al. 2015; Diefenderfer et al. 2012). A LiDAR dataset developed for the U.S. Army Corps of Engineers has permitted the delineation of wetland channel networks (e.g., Diefenderfer et al. 2008). However, a prior pilot study of potential climate change impacts on the Corps' $150 million FY08-FY18 commitment to wetland restoration in the Columbia River Estuary focused on the program goals for juvenile salmon as an outcome and not shoreline protection; lacked data on regulated river flows for analysis, despite extensive hydroelectric development in the basin; and examined only three sites in the 234-river-kilometer tidal river and estuary (USACE 2013). Through workshops and webinars and group discussions, the aforementioned study concluded, "because climate change is multi-faceted and complex it is important for robust ecosystem restoration to identify the habitat and species sensitivity to climate change conditions." We propose to address the habitat component of this information need through wetlands or NNBFs.

Coos Estuary Study Area. Tidal wetland restoration efforts have been implemented at various sites in the Coos Estuary over the past 20 years. Projects developed by South Slough National Estuarine Research Reserve (South Slough NERR) and local partners were undertaken with expert advice provided by estuarine wetland scientists through regular technical advisory committee meetings. The Coos Watershed Association (CoosWA) used similar methods in their implementation of the Matson Creek restoration project in the upper Coos Estuary. Like the Grays Bay projects described above, the documentation and analyses of South Slough NERR and CoosWA restoration efforts provide the proposed modeling (hydrodynamic modeling in Task 2 below) with valuable local context for the development of restoration scenarios (Cornu 2005a-c, Cornu and Sadro 2002). Proposed modeling will also be informed by the results of the experimental restoration approaches taken at several sites (e.g., establishment of multiple marsh surface elevations), as well as other relevant estuarine wetland research undertaken by South Slough NERR research staff (e.g., sediment dynamics research using a network of 23 surface elevation tables (SETs) established starting in 1994, and the monitoring results associated with the 2009 establishment of five “sentinel sites” used to track physical and biological responses to long-term SLR in least-disturbed tidal wetlands). Multiple cores have been dated in both least-disturbed and restored wetlands, as well as limited GHG sampling, across salinity gradients in Coos Bay by co-PIs Bridgham and Sutherland (Johnson et al., submitted, and unpublished data).

In both estuaries we will consider two to three plausible NNBF restoration scenarios over the next 30-50 years in the estuaries as a response to management decisions and tradeoffs about coastal land use (e.g., Mills et al. 2018). Restoration scenarios will be developed with input from the primary project supporters of this proposed research (Attachment: Letters of Support). The baseline scenario at each estuary will be a “business as usual” scenario where no additional restoration (beyond projects that have already been implemented to date) will be conducted in either estuary. Additional scenarios will involve increasing proportions of restored land that is currently within elevation ranges suitable for tidal inundation over the next 10-20 years. We will work with key research and management organizations in each study region to help develop the additional scenarios (e.g., South Slough NERR and CoosWA in the Coos Estuary, and Columbia Land Trust in Grays Bay) by identifying likely land parcels that can be restored in each region.

Corresponding to the time horizons of the NNBF restoration scenarios, we will synthesize at least two reasonable scenarios for SLR in the study areas as a function of land-surface elevation change, eustatic sea-level change, and river-basin hydrological change. We will make use of recent information, data products, and scenarios including NOAA’s National Ocean Service scenarios for the West Coast (Sweet et al. 2017), and detailed local projections of SLR and land-surface movements for Washington State developed through NOAA’s Regional Coastal Resilience Grants Program (Miller et al. 2018). We also anticipate regulated Columbia River flow climate change scenarios to be available before or during the proposed study to provide boundary conditions for Grays River modeling.

Task 2: Hydrodynamic modeling of coastline protection

We will use hydrodynamic models to evaluate the degree of shoreline protection conferred by coastal wetlands of different vegetation types in Coos Estuary and Grays Bay. To determine thresholds for coastal protection services accorded by PNW tidal wetlands (research question 1), we will examine flood protection across wetlands varying in age, salinity, elevation, and vegetation type. We will use SLR scenarios (Task 1) with 3-D, high-resolution models already developed for Coos Estuary (Conroy 2018; Sutherland and O’Neill 2016) and Grays Bay (Diefenderfer et al. 2012), to assess coastal inundation during typical monthly spring tides and extreme events. Additionally, under the different SLR scenarios, we will vary the terrain and bed friction coefficients according to the decoupled wetland succession model to assess relative barrier functions of NNBFs. Finally, we will analyze uncertainty in the models, and the effects of inter-annual hydrologic variability and other factors on vegetation. We plan to use the Finite Volume Coastal Ocean Model (FVCOM; Chen et al. 2012) for all simulations. FVCOM uses a finite volume discretization of the three dimensional, hydrostatic, primitive equations on an unstructured grid, allowing high resolution in the main channels (15 m horizontal spacing) and coarser resolution in the coastal ocean. FVCOM also allows wetting and drying of grid cells, which is essential for testing SLR scenarios in tidal estuaries. We will conduct hydrodynamic modeling analysis of current conditions and alternative SLR scenarios developed in Task 1. The year representing current conditions will be chosen based on the availability of data to support the hydrodynamic and WARMER (Task 4) modeling. To provide enough information to evaluate the effects on vegetation through a growing-season cycle, evaluate effects of fall-winter storms and surges, and to drive the WARMER model, we will use an approximately one-year simulation period. Only the tidal boundary conditions for the SLR scenarios will be altered for each of the SLR scenarios, with upstream inflows remaining the same.

Coos Estuary. We will build on the hydrodynamic modeling work done by co-PI Sutherland and his colleagues examining present-day estuarine dynamics (Conroy 2018). In addition, the FVCOM model for Coos Estuary has already been run successfully for several different geometry and bathymetry configurations to explore a proposed channel modification project, as well as historic conditions before jetties were built and prior to dredging. These simulations give confidence that a similar setup and modifications due to different SLR scenarios or vegetation/elevation changes per restoration scenarios could be accomplished. At present, the Coos Estuary bathymetry (Conroy 2018) is built off a NOAA DEM, with extensive additional data taken from coastal LiDAR and single-beam echosounder surveys conducted in the narrow and shallow sloughs (Ruggiero et al. 2005). Model boundary conditions for Coos Estuary will include river discharge at fourteen locations within the estuary, tidal forcing at the open boundary (TXPO Tidal Model Driver; Egbert and Erofeeva, 2002), and salinity at the open boundary from a regional ocean model (Giddings et al. 2014). Most freshwater enters the estuary through the Coos River (composed of S. Fork Coos River, W. Fork Millicoma River, E. Fork Millicoma River, and Marlow Creek), which is the only gauged freshwater input to the estuary. The freshwater input from the remaining smaller creeks is estimated based on relative watershed area from CoosWA. Our present day run goes for the calendar year 2014 and has been validated using extensive observations from the estuary.

Grays Bay. We will base hydrodynamic modeling for Grays Bay and its tributaries on an existing FVCOM hydrodynamic model used to examine various geometry configurations of wetlands restoration (Thom et al. 2018). Channel and floodplain topography/geometry have been developed from surveyed cross sections and LiDAR data, and wetland topography and configurations have been added for two wetland restoration projects (Kandoll and Mill Road). We will update the configurations as needed based on as-built conditions in consultation with the Columbia Land Trust. For example, we will add the topography and configuration of additional wetlands such as Secret River, Crooked Creek, Johnson Property, and Deep River based on prior PNNL-surveyed RTK-GPS data and LiDAR data of the U.S. Army Corps of Engineers'. The FVCOM model includes boundary conditions to account for riverine inflows and a tidal/water surface elevation boundary condition at the mouth of Grays Bay that interfaces with the Columbia River. The river/stream inflows from upland drainage (Grays River and Deep River, and smaller creeks such as Secret River and Crooked Creek) reflect freshwater runoff from precipitation/rainfall on the Grays River watershed. We will use Grays River inflows from the stream gage located at the upstream end of the Grays River model domain. Tidal/water surface elevation inflows reflect the varying water level at the mouth of Grays Bay due to tidal influences, SLR, and releases from upstream dams (Bonneville) on the Columbia River. We will derive tidal (and salinity) boundary conditions from current hydrodynamic modeling of the Columbia River expected in November, 2019 from joint PNNL-Portland State University research for the Bonneville Power Administration.

To quantify the uncertainty of the analyses for this study, we will use a logic tree to evaluate the effect of combinations of components/parameters model outcomes. This approach carries the uncertainties through the FVCOM modeling and analysis. The epistemic uncertainty analysis is based on approaches from seismic risk analysis, as recently applied by the U.S. Nuclear Regulatory Commission in storm surge flood hazard analyses. Components of the approach will be transferred to this study of co-benefits from wetlands management for resilience to relative SLR. An example logic tree (Fig. 4) shows the primary components of a logic tree analysis, which could include the following: SLR scenarios, hydrodynamic modeling error, hydrodynamic model results integration/averaging, the ecological model productivity, and the ecological model decomposition rate. The logic tree produces a range of outputs, and the spread of these outputs (e.g., standard deviation and range) indicates the degree of epistemic uncertainty in the analyses. It should be noted that the components to include in uncertainty quantification will be developed by the study team as informed by sensitivity tests of potential components. Components which produce little change can be fixed at a specific value (and so have no effect on the range of outputs from the logic tree analysis), while those that produce larger changes can be included in the logic tree. We will also include model error (estimated from calibration and verification) by comparison of the observed and modeled results.

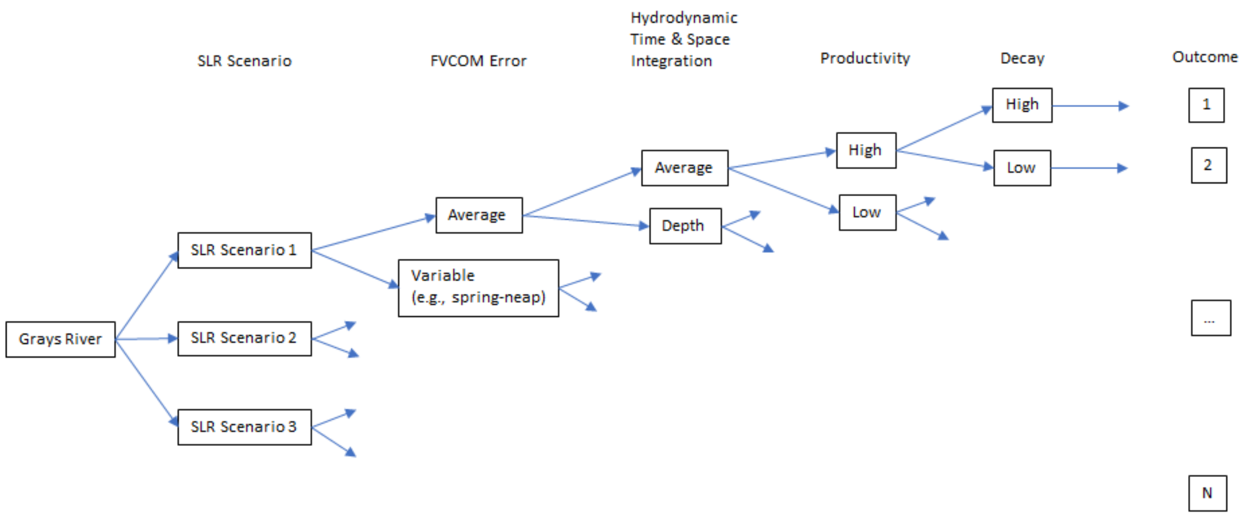

Figure 4. Example logic tree in the FVCOM hydrologic model.

Task 3: Evaluation of GHG emission and carbon sequestration rates by land type, elevation, and salinity

To assess restoration and SLR impacts on GHG emissions (carbon dioxide, methane, and nitrous oxide) and carbon sequestration rates (research question 2), we will compile existing data from disturbed, restored, and reference (least-disturbed) wetlands in both estuaries and supplement these datasets with additional emissions and sequestration rate measurements along inundation, salinity, and land-use gradients. A full blue carbon accounting of wetland restoration requires knowledge of historical soil carbon loss in disturbed sites and their current GHG emissions, as well as soil carbon sequestration rates and GHG emissions in restored sites. To allow extrapolation across the landscape, this information needs to be collected in restored sites of varying ages across salinity gradients. Over time restored wetlands will accumulate sediment and thus move higher in the tidal frame, typically progressing from mudflats to low marshes to high marshes or tidal swamps. By sampling least-disturbed sites, we will be able to model the changes in sedimentation and soil carbon sequestration rates and GHG emissions as the restored wetlands undergo natural succession, assuming at maturity they functionally act similar to least-disturbed wetlands. We will statistically model GHG emissions relative to ecosystem drivers such as groundwater height, salinity, pH, soil carbon and nitrogen content, and plant community type so that we can estimate changes in GHG emissions as the restored wetlands mature over time. We will compare a number of modeling techniques for their success in predicting GHG emissions, including classification and regression trees (a nonparametric approach), structural equation modeling, and hierarchical partitioning of multivariate models. The PIs have used all of these techniques successfully previously.

It is particularly important to account for GHG emissions when examining the climate forcing benefits of wetland restoration because the sustained-flux global warming potential over 100 years of methane is 45 and of nitrous oxide is 270 (Bridgham et al. 2006, Neubauer and Megonigal 2015). Thus, for every gram of methane or nitrous oxide emitted from a wetland, more than 45 and 270 grams of soil carbon need to be sequestered, respectively, for net carbon sequestration. Fortunately, many diked former estuarine wetlands along the outer coast that currently have low to zero salinity with high emissions of methane and nitrous oxide may experience reduced methane emissions upon restoration because of the inhibitory effect of increasing salinity on methanogenesis, providing a positive climate forcing benefit in addition to any carbon sequestration in soils and vegetation (Poffenbarger et al. 2011). The effect of salinity is actually indirect and reflects the degree to which sulfate reducing bacteria outcompete methanogens (Bridgham et al. 2013, Poffenbarger et al. 2011). Sea water has high sulfate concentrations compared to most fresh water sources, and salinity acts as an easily measured proxy for the oceanic contribution to surface and pore water. However, very little of this research has been done in restored wetlands, and none in the PNW until the recent efforts described below. Our preliminary results in Oregon estuaries indicate some, but not all, restored mesohaline and polyhaline wetlands can emit substantial amounts of methane (Schultz et al. 2018) for reasons that need to be further explored in the proposed research.

There are limited GHG data in PNW estuarine wetlands from disturbed, restored, and least-disturbed wetlands, and none to our knowledge exists in tidal freshwater systems such as Grays Bay. Existing GHG data are available from a few disturbed, restored, and least-disturbed sites of a range of ages, salinities, and salinity regimes in both Coos and Tillamook Bays along the southern and northern outer Oregon coast, respectively (Bridgham and Schultz, unpublished and Schulz et al. 2018) and from the large Snohomish restoration in Washington's Puget Sound (Windham-Meyers, unpublished data). To better encapsulate the spatial and temporal variability in GHG emissions, we will conduct additional measurements at a range of elevations and land types. In Grays Bay, we will sample in least-disturbed low marsh, high marsh, and tidal swamp habitats (2-3 sites each), currently diked/drained sites (3), and restored sites (3), with six sampling locations at each site. We will sample each site 9-10 times over one year to obtain integrated annual estimates of GHG fluxes. To supplement existing data, we will sample additional sites in Coos Bay to assess the interaction between land-use and salinity. We currently have limited seasonal sampling (6 time points) of GHG fluxes in Coos Bay in 3 restored mesohaline marshes at different tidal heights; 1 least-disturbed mesohaline marsh; 1 disturbed, 1 restored, and 1 least-disturbed polyhaline marsh; and 1 disturbed, 1 restored, and 1 least-disturbed freshwater marsh (Schultz and Bridgham, unpublished). We will collect 4 additional time points for these sites. Additionally, we will sample 1 new least-disturbed mesohaline marsh and 2 new disturbed, restored, and least-disturbed polyhaline site to provide for more site replication. These new sites will be sampled 10 times over one year. We will use a Gasmet DX4040 Fourier Transform Infrared (FTIR) gas analyzer to measure fluxes of methane, nitrous oxide, and carbon dioxide (representing ecosystem respiration) in dark chambers. This system allows for the integration of gas concentrations measured at 10 Hz in a closed-loop system over typically 30 seconds to 1 minute, providing robust estimates within a chamber in a 10 minute period. We have found that we can measure quite small fluxes with confidence given the many time points taken.

We will assess carbon sequestration rates and sediment accretion rates for carbon accounting and WARMER modeling (task 4 below) by using existing data and collecting additional cores as described below to develop a comprehensive data set across habitat types, estuaries, and salinity regimes. All of the previously-measured GHG sites in Coos Bay have soil carbon concentrations, bulk density, and estimates of sediment accretion rates through a combination of SETs, deep cores for ^{137}Cs and ^{210}Pb radiometric dating (Drexler et al. 2018), and for some restored sites, age of restoration and depth of freshly accreted sediment over the former soil surface (Bridgham et al., unpublished data). Many of the new sites in both Coos Estuary and Grays Bay already have extensive data on plant communities and soil carbon densities, and groundwater well infrastructure as part of the NERRS Science Collaborative Stocks project (USACE 2000; Janousek et al., unpublished). Several also already have deep cores taken from them and stored for dating that would be done as part of this project. Where needed, at select new sites, we will collect additional deep cores to assess soil carbon stocks. In some restored sites, the freshly accreted sediment is readily apparent over a compacted clay layer, making it straightforward to calculate the average accretion rate since restoration. For sites with a less clear pre-restoration surface or if the exact date of restoration is unknown, we will install feldspar marker horizons to determine accretion rates over 2 years. Between existing data and new samples, we aim to compile approximately 3-4 cores per habitat type (marsh, tidal swamp) per salinity regime (freshwater, mesohaline, polyhaline) per estuary for evaluation of spatial variation in accretion rates.

We will collect data on key ecosystem drivers at sites where we assess GHG emissions and carbon sequestration rates. We will generate high-frequency time series of water level, temperature, and salinity of wetland groundwater using groundwater wells with automated sensors following methods in use for the NERRS Science Collaborative stocks project. Additionally, we will collect time series (hourly) measurements of near-surface soil temperatures using small automated Onset Hobo sensors.

Task 4: Modeling SLR effects on elevation change in restored and reference wetlands (WARMER)

At the Coos Bay and Grays Bay study sites, we will model future projections of wetland elevation change under SLR scenarios using the Wetland Accretion Rate Model of Ecosystem Resilience (WARMER; Swanson et al. 2014, Thorne et al. 2018), a sediment cohort model, under a range of sea-level rise scenarios. Model outcomes will help us link projections of wetland elevation change with information on change in coastal protection, GHG emissions, and carbon sequestration in different SLR scenarios. In Coos Estuary, we will run WARMER across the sea-level rise scenarios used for the hydrodynamic modeling (Task 1) for 1-2 least-disturbed marsh site and 1-2 restoration sites for each of three major salinity regimes present in the estuary: tidal fresh/oligohaline, mesohaline, and polyhaline conditions. In Grays Bay, we will run WARMER at two or more wetland parcels in the following land use classes: least-disturbed tidal marsh, least-disturbed tidal swamp, restored tidal wetland (all sites in the area are fresh/oligohaline).

Major parameter inputs into WARMER include present-day wetland digital elevation models (DEMs), sea-level rise rate (scenarios), mineral accretion rate, above-ground annual production rate, and organic matter decomposition rate. We will use RTK-GPS and LiDAR-based elevation data from both estuaries to construct DEMs for wetland parcels to be modeled. Where LiDAR datasets are used, we will adjust returns for vegetation interference (e.g., Buffington et al. 2016). To parameterize the models so that they are site-specific for each major wetland type (marsh versus forested tidal swamp) and salinity regime (fresh/oligohaline, mesohaline, polyhaline) in the Coos Estuary, we will compile sediment accretion rate data from existing data (SET table, core, and sediment pin methodologies) and the additional cores analyzed in Task 3. Using these datasets we will fit accretion-by-elevation curves for each combination of wetland type and salinity regime (e.g., Thorne et al. 2018).

To determine variation in productivity along elevation gradients, we will use regional information on these relationships for the Coos Estuary (Janousek et al. 2016), and production rate data obtained from biomass clippings (Diefenderfer et al. in preparation) from the Grays River study area. We will also synthesize decomposition data from sites in or near the near Grays River and Coos Bay areas (Hanson et al. 2015; Janousek et al. 2017, Janousek et al., unpublished). Using the parameterized models, we will run WARMER in annual time steps for each wetland parcel across the matrix of sea-level rise and restoration scenarios developed in Task 1, and process outputs in 10-20 year time steps to the year 2120. To evaluate uncertainty in the WARMER ecological model, we will vary major model parameters (above- ground productivity, root-to-shoot biomass ratios, and decay constants) based on ranges of values from the literature obtained from wetlands in the Pacific Northwest region (Janousek et al. 2016, Thorne et al. 2018) and incorporate these uncertainties into the hydrological uncertainty analysis described in Task 2.

Task 5: Landscape-scale synthesis and application for NNBF planning & management

The final task in this project will constitute a synthesis of model outputs, field measurements, and other information in summary materials for target end users: wetland owner-managers, restoration and mitigation program managers, restoration practitioners, environmental engineers, coastal planners, and other scientists. Our end users have expressed great interest in policy and management outcomes of the overall outputs of our research: increased understanding of the degree to which conserving and restoring tidal wetlands helps improve SLR-resilience of coastal communities in the PNW, and evaluating how wetlands respond ecologically to SLR including potential GHG exchange co-benefits (Attachment: Letters of Support). Representatives of six organizations (federal, state, and NGO) described the utility of filling these data gaps to help reduce uncertainties in specific outcomes they oversee, especially prioritizing sites for current, planned, and other future acquisition and restoration initiatives.

To facilitate analysis and communication of project results, we will develop a spatial data package in ArcGIS, representing each SLR-by-restoration scenario at the landscape scale (i.e., Fig. 1 insets), with hydrodynamic and WARMER model outputs, using a change analysis approach (Borde et al. 2003a). We will analyze hourly water surface elevation data outputs from FVCOM models to evaluate potential impacts to vegetation, using methods including the sum exceedance value (Jay et al. 2016) and examining the potential resilience of forested wetlands and marshes based on previously established inundation-elevation relationships. We will contrast the relative influence of SLR and restoration on outer coast and fluvial tidal wetlands. The epistemic uncertainty analysis will inform the understanding of risks relative to storm protection of coastal communities and transportation corridors, co-benefits, and wetland resilience.

In response to end user needs, we will develop fact sheets and summaries of restoration and SLR scenarios (outputs) for each study area including a compilation of model outputs across the range of scenarios for select marsh and forested tidal swamp locations (including restoration sites) considered in the study. We will identify opportunities and constraints for future wetland restoration projects in each of the study areas and management implications of modeling outputs, and include projections of how both coastline protection afforded by tidal wetlands and blue carbon sequestration may change in the future under each scenario. We will request preliminary review of products from authors of letters of support for this proposal. We will present final results, including summaries and fact sheets (e.g., Borde et al. 2004), in a half-day online meeting with key regional stakeholders including the U.S. Army Corps of Engineers Portland District, South Slough National Estuarine Research Reserve System, watershed councils in OR and WA, OR Department of Land Conservation and Development, and Bonneville Power Administration. We will also present results from the project at the biennial Columbia River Estuary Conference in Astoria (2022) (attended by BPA and USACE) and other regional and national conferences (e.g., Restore America's Estuaries, Coastal and Estuarine Research Federation, Pacific Estuarine Research Society) (e.g., Borde et al. 2003b). Additionally, we will compile results in peer-reviewed journal articles including one detailing the hydrodynamic modeling results (led by Sutherland and Breithaupt), one or two publications on SLR and land-use impacts on GHG and carbon sequestration rate measurements (led by Bridgham and Janousek), and one on WARMER model results (led by Janousek, Diefenderfer, and Borde).

Ongoing management studies will provide important data for the regionalization of our research results, including assessments of the extent of former tidal wetlands in PNW estuaries (http://www.pacificfishhabitat.org/data/tidal-wetlands-loss-assessment/), wetland zonation in the Columbia River estuary (Jay et al. 2016; Borde et al. in review), and studies that prioritize wetland restoration for specific areas (Ewald and Brophy 2012). These existing efforts provide valuable data, analysis, and experience for evaluation of the broader landscape-scale context of our restoration scenarios and results of our modeling and analyses.

Value to the EESLR program goals

Our project contributes to the EESLR program goals by providing integrative applied and basic coastal science to assess impacts of SLR to PNW ecosystems and communities. Our research will provide projections of how protective and non-protective ecosystem services are likely to change under realistic restoration scenarios and a range of potential SLR scenarios in the future. These data will help coastal managers and planners assess the impacts and tradeoffs of different management decisions for the protection of coastal wetlands and resources.

Our research will provide insight into the potential long-term role of least-disturbed and restored wetlands - key types of natural and nature-based features in the PNW - in sustaining important services for regional communities. It addresses a key research need of the EESLR program, namely the lack of research on “the benefits and performance of NNBF”, including “during extreme and chronic events and how these benefits vary with coastal landscape variables such as topography.” The roles of NNBF in providing a resilient future for protection of human communities and ecosystem services is particularly poorly studied in the PNW relative to other parts of the U.S., so our research fills an important geographic knowledge gap for the ESSLR program.

This proposal combines both field-based and modeling based research to address the services rendered by NNBF in the PNW, consistent with the focus of a dual approach by the EESLR program. We address priorities 2 and 3 of the current NCCOS-EESLR proposal solicitation:

- Determining how coastal ecosystems and their services are vulnerable to SLR across a range of NNBF scenarios
- Evaluation of a key non-protective ecosystem service (GHG emissions and blue carbon sequestration) in major NNBF wetland types in the PNW (restored and least-disturbed wetlands).

Role of each Principal Investigator

Dr. Christopher Janousek (OSU) will lead the research team and be responsible for coordination of project implementation and project outcomes and deliverables. He will work with co-PIs to develop restoration scenarios (Task 1), implement WARMER modeling and GHG and carbon sequestration rate measurements in the field (Tasks 3,4), and synthesize results of the project (Task 5). He will co-supervise an OSU technician who will be responsible for implementation of GHG measurements, field sediment collection, maintenance of ecosystem driver measurements, and assistance with WARMER model runs.

He will lead implementation of the data management plan and be responsible for periodic communication with the federal project manager.

Dr. Heida Diefenderfer (PNNL) will co-develop spatially explicit landscape-scale restoration and sea level rise scenarios for the Grays Bay study area (Task 1), help identify sediment and water data previously collected at Grays Bay study sites, provide technical input on WARMER modeling and review model outputs (Task 4), contribute to the final synthesis and serve as stakeholder liaison for engagement and outreach activities related to outcomes through the Columbia Estuary Ecosystem Restoration Program (Task 5). She also will serve as the project manager for PNNL and be responsible for coordinating PNNL's execution through the multi-partner team effort, overseeing budget control, outputs, and reporting.

Dr. Stephen Breithaupt (PNNL) will co-lead the hydrodynamic modeling analysis for the Grays River and Grays Bay in coordination with Dr. David Sutherland (Task 2). He will provide input files, technical guidance and review for implementation of the hydrodynamic modeling analyses of the Grays system including any updates to the PNNL model grid, development and implementation of SLR scenarios, boundary conditions, and data processing to support the WARMER modeling analyses (Task 4).

Ms. Amy Borde (PNNL) will co-develop spatially explicit landscape-scale restoration and sea level rise scenarios for the Grays Bay study area (Task 1). She will identify and contribute sediment, plant community cover, vegetation biomass, and water data previously collected at Grays Bay study sites, plus provide technical input on WARMER modeling and review model outputs (Task 4). She will lead analysis using geographic information systems (GIS) for the final synthesis (Task 5) and participate in engagement and outreach activities related to the Columbia Estuary Ecosystem Restoration Program.

Mr. Craig Cornu (IAE) will coordinate stakeholder engagement with end-users during this project, including the review of interim products and feedback by primary project supporters. He will also provide technical support to the development of restoration and SLR scenarios for Coos Bay and the synthesis of results in GIS (Tasks 1,5).

Dr. Scott Bridgham (UO) will lead the GHG flux measurements and collaborate in collection of the ecosystem driver measurements (Task 3). He will also collaborate in collection of soil accretion and soil carbon sequestration data in Coos Estuary and lead in ^{210}Pb and ^{137}Cs dating of cores from both sites at UO. As part of this activities, he will work closely in coordinating the efforts of the OSU technician with Dr. Janousek. He will work with Dr. Janousek to incorporate the GHG flux data with the WARMER modeling.

Dr. David Sutherland (UO) will lead the hydrodynamic modeling of the two estuary systems (Task 2). He will work with all co-PIs on developing the model grids, parameters, and scenarios to test. He will supervise a technician at UO who will be responsible for the model testing and scenario runs, in addition to a continuing PhD student, Maria Jose Marin Jarrin, who is presently working on Coos Estuary hydrodynamics.

Application to management

With widespread tidal wetland restoration efforts ongoing throughout the PNW, there is a significant management need for actionable scientific information on the impacts of SLR to estuarine ecosystems. This need includes assessments of natural resource vulnerability to climate change and how wetland functions and services may change into the future with SLR. Our proposal addresses two key wetland services - coastal protection and coastal blue carbon - of growing importance to wetland managers and policy makers throughout the region.

Using our existing local and regional end user contacts, including colleagues associated with the PNW Blue Carbon Working Group, we will ensure project results are relevant to the needs of regional stakeholders including the Columbia Estuary Ecosystem Restoration Program (U.S. Army Corps of Engineers & Bonneville Power Administration), Federal Emergency Management Agency, Federal Highway Administration , US Fish and Wildlife Service, NOAA, Oregon Department of Fish and Wildlife, Oregon Department of Land Conservation and Development's Coastal Management Program, Oregon Watershed Enhancement Board, Washington Department of Fish and Wildlife, Washington Department of Natural Resources, the Cowlitz Tribe, Coos Bay's Partnership for Coastal Watersheds, Coos Watershed Association, South Slough National Estuarine Research Reserve (NERR), Padilla Bay NERR, Columbia Land Trust, and other partners.

End user engagement in the project will help refine landscape-scale restoration scenarios and promote dialogue with stakeholders on issues of coastal resiliency, SLR, and blue carbon science. Moreover, working with end-users, this project will help develop forward-looking restoration and management options for local land management and resiliency-building and deliver science results to those implementing NNBF in their coastal communities. Partners will help us identify the types of data synthesis and deliverables that will be of greatest utility for ongoing coastal wetland management (Task 5). This project will advance ecosystem modeling of SLR effects on coastal protection and blue carbon services of NNBFs in the PNW. Furthermore, by evaluating the multi-functional benefits achieved by restoration, this study is expected to inform site-selection for new NNBFs and provide sound information for decision makers working on the ecological, economic, social, and management dimensions of tidal wetland restoration.

In summary, the primary project *outputs* will be: 1) annual and final project reports to NCCOS; 2) three to five manuscripts suitable for publication in the peer-reviewed literature; and 3) the technical outputs on which these written outputs are based: hydrodynamic modeling outputs, WARMER modeling outputs, and spatial datasets including the landscape-scale restoration and SLR scenarios and final project synthesis. We will summarize project outputs for end users in fact sheets and summary documents to be presented at a dedicated half day workshop and shared at at various relevant regional and national professional conferences.

Based on our preliminary conversations with project end users, we anticipate the project's *outcomes* to include greater understanding of the elevation range(s) at which outer coast and lower Columbia River tidal wetland restoration projects should be designed and constructed to maintain ecosystem functions as sea levels rise. Specifically, we anticipate that project results will inform restoration planners as they identify a range of target tidal wetland elevations that increase the long-term resiliency of restoration projects facing a range of future SLR scenarios. Importantly, project results will also improve the accuracy of long-term valuations for blue carbon financing, an emerging need in the PNW. In addition, we anticipate that project results will be useful for coastal wetland funding program managers to help them incorporate better informed SLR resiliency requirements into their program guidance and to encourage the development of restoration and conservation proposals that include multiple ecosystem services co-benefits. Managers from funding programs that support restoration project effectiveness monitoring (e.g., Oregon Watershed Enhancement Board, US Fish and Wildlife Service, NOAA Restoration Center) may also be able to use outcomes from our research to foster project monitoring that tests our project's model outputs over time so they can be fine tuned for the benefit of stakeholders into the future. By including both land managers and funding program managers as project end users, we anticipate project outputs will have broad and long lasting *outcomes* for landscape-scale coastal restoration and conservation planning in the Pacific Northwest and perhaps outside the region.

Data management plan

Types of data generated: This project will use and generate various types of data including field point measurements (wetland elevation, accretion rates), lab instrumentation checks (automated loggers), time series measurements (GHG fluxes, soil temperatures, groundwater salinity and water levels), geospatial layers (e.g., digital elevation models, model domains), and numerical model fields (4-D, space and time).

Data analyses: We will conduct data processing and analyses in standard software including Excel spreadsheets, Hoboware and Odyssey software (logger time series), MATLAB, and R. We will conduct hydrodynamic modeling with open source code (FVCOM), WARMER model implementation and statistical analyses in R, and geospatial analyses in ArcGIS.

Data and instrument QA: We will use appropriate data quality checks and quality assurance to ensure that data used from outside sources, or generated by the team in the course of the project are reliable and suited for analyses and project goals. For field measurements these will include analysis of appropriate analytical standards (GHG measurements) and instrumentation checks (logger checks under controlled conditions, RTK checks on benchmarks).

Data transcription, storage, and backup: We will store all data in common digital formats including .txt, .csv, .xls(x), and shapefiles. We will store analytical scripts in .R files. During project execution, data will be stored on hard drives and backed-up periodically onto external hard drives, servers, or cloud data storage. We will append pertinent metadata to files and/or folders where datasets are stored. For the model, FVCOM is compliant with the NetCDF Climate and Forecast (CF) 1.0 metadata conventions. As such, all input (grid, surface forcing and boundary conditions) and output (physical and biological fields) files associated with FVCOM are already following an accepted standard for processing and sharing model information. CF conventions are increasingly gaining acceptance and have been adopted by a number of projects and groups as a primary standard.

Metadata standards: We will annotate individual data files (or groups of files in folders) and analytical scripts with metadata appropriate to the type of data including date, author, data status (final or provisional), contact person, and other relevant information. For geospatial data, we will use the FGDC CSDGM metadata standard. For numerical model data, the existing CF conventions define metadata that provide a definitive description of what the data in each variable represents, and the spatial and temporal properties of the data. This enables users of data from different sources to decide which quantities are comparable, and facilitates building applications with powerful extraction, re-gridding, and display capabilities (http://cf-pcmdi.llnl.gov).

Data sharing and archiving: We will make all datasets and scripts from the project available to any interested individual or institution once data sets have been appropriately QA/QC checked and a reasonable amount of time has elapsed for the opportunity to publish the datasets (typically 12-18 months after finalization of the data set). There is no centralized repository for oceanographic model data. If requested, access to the raw, unprocessed, model output will be provided via contact with the lead PI. All model output will, in principle, be readily available for access and sharing as soon as is reasonably possible after processing and will be preserved for at least five years beyond the award period, as required by NOAA guidelines. The model code, with extensive documentation, is open source and has a large, active online communities, available at http://fvcom.smass.umassd.edu/.

Additionally, for each dataset associated with a peer-reviewed article, we will make data publicly available upon publication, in open public repositories such as Dryad or OSU ScholarsArchive. We will submit manuscripts to open access journals where funding permits.

Publications: We will report the findings of this project in annual and final reports to NOAA and in three or more manuscripts to peer-reviewed journals.

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DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS, PORTLAND DISTRICT
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National Centers for Coastal Ocean Science
1305 East West Highway
Silver Spring, MD 20910

January 4, 2019

To Whom It May Concern:

I am writing to express my support for the project titled, "Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands," submitted to NOAA/NCCOS's Ecological Effects of Sea Level Rise grant program. A project such as this will help Pacific Northwest coastal decision makers evaluate whether conserving and restoring tidal wetlands makes coastal communities more resilient to changing sea level rise (SLR). I am particularly interested in the project's objective to evaluate how key attributes of natural and nature-based features—elevation, vegetation composition, and time since restoration—respond to coastal SLR.

For over 15 years, the USACE has co-led implementation of the Columbia Estuary Ecosystem Restoration Program (CEERP), an ecosystem-based program focused on restoring tidal wetlands in the 1500 km^2 floodplain of the tidal river and estuary, from the mouth of the Columbia River to river kilometer 234, at Bonneville Lock and Dam. Tidal wetlands in the Columbia River functionally support juvenile salmon, a key indicator species under the CEERP, but we acknowledge they also provide other critical functions, e.g., providing natural barriers to coastal storm surges, sequestering carbon, and buffering or storing floodwaters. Several tidal wetland restoration projects in the vicinity of the Grays River, a tributary to the Columbia, are part of the CEERP. We have previously successfully collaborated with a proposal team member, Pacific Northwest National Laboratory, on research and hydrodynamic modeling in the Grays Bay. Their products and service has always been exemplary.

I am confident by applying a hydrodynamic model to quantify the co-benefits of tidal wetland restoration this project will advance our understanding of wetland development (i.e., the trajectory of response) and potential SLR resilience. The project's results will be readily applicable. It will lead us to better identify and prioritize land acquisitions; and more effectively and efficiently deliver civil works wetland conservation and restoration studies, designs and projects.

Thank you for the opportunity to express my support for this important line of investigation.

Sincerely,

Cynthia A. Studebaker
US Army Corps of Engineers, NW Portland District (CENWP)
CEERP Research and Monitoring Lead

HEADQUARTERS
850 OFFICERS' ROW
VANCOUVER, WA 98661

Columbia Land Trust
CONSERVING THE NATURE YOU LOVE

CONTACT
TEL: 360.696.0131
FAX: 360.696.1847

January 8, 2019

National Centers for Coastal Ocean Science
1305 East West Highway
Silver Spring, MD 20910

To Whom It May Concern:

I am writing to express my enthusiastic interest in and support for the Oregon State University-led team's proposal, "Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands," submitted to NOAA/NCCOS's Ecological Effects of Sea Level Rise grant program. Columbia Land Trust is very interested in supporting this research designed to help Pacific Northwest coastal decision makers evaluate whether sea level rise (SLR) will affect the utility of conserved and restored tidal wetlands for helping make coastal communities more resilient to the effects of SLR. We are particularly interested in the team's proposed objective to evaluate how key attributes of natural and nature-based features–elevation, vegetation composition, and time since restoration–affect coastal protection related to SLR.

For almost 30 years, Columbia Land Trust has been a conservation leader along the lower 250 miles of the Columbia River. The Land Trust has been deeply involved in the acquisition and restoration of multiple properties in the Grays Bay study area of the proposed project. To date the Land Trust has conserved over 1,400 acres around Grays Bay and have plans for restoring an additional 450 acres being restored in the near future. We work closely with the Columbia Estuary Ecosystem Restoration Program, which is focused on restoring tidal wetlands in the 1500 km^2 floodplain of the tidal river and estuary from the Pacific Ocean to river kilometer 234 at Bonneville Lock and Dam. Tidal wetlands on the Columbia and elsewhere in the Pacific Northwest provide key habitat functions for juvenile salmon and other potential functions such as providing natural barriers to coastal impacts such as storm surge, sequestering carbon, and buffering or storing floodwaters. We have previously successfully collaborated with a proposal team member, Pacific Northwest National Laboratory, on research, hydrodynamic modeling, and wetlands management studies in the Grays Bay area. Columbia Land Trust is interested in the results of future research and model applications to quantify co-benefits of tidal wetland restoration, increase understanding of the trajectory of restored wetland development, and improve understanding of the resilience of natural and restored wetlands to sea level rise. We work closely with the local community to find common ground between habitat conservation and community resilience. The proposed project work will help inform and guide this effort.

Columbia Land Trust and our community partners would benefit from this project's proposed evaluation of the likely effects of SLR on various landscape-scale designs for tidal wetland restoration and the specific ecosystem services associated with least-disturbed and restored tidal wetlands near Grays Bay, WA. The results would be useful in refining the identification and prioritization of land acquisitions and management, including selection of restoration designs based on potential future resilience. We look forward using the results of this project to help us evaluate the utility of tidal wetland conservation and restoration as cost-effective, multi-beneficial strategies for improving resilience to SLR on the Columbia estuary floodplain.

Thank you for the opportunity to express our support for this important project.

Sincerely,

Ian A. Sinks
Stewardship Director

Department of Energy

Reading File

Bonneville Power Administration
P.O. Box 3621
Portland, Oregon 97208-3621

ENVIRONMENT, FISH AND WILDLIFE

1/14/19

In reply refer to: Jason Karnezis - EWL-4

National Centers for Coastal Ocean Science
1305 East West Highway
Silver Spring, MD 20910

To Whom It May Concern:

I am writing to express my strong interest in and support for the proposal, "Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands," submitted to NOAA/NCCOS's Ecological Effects of Sea Level Rise grant program by an Oregon State University-led team. Bonneville Power Administration is very interested in supporting this research designed to help Pacific Northwest coastal decision makers evaluate whether sea level rise (SLR) will affect the utility of conserved and restored tidal wetlands for helping make coastal communities more resilient to the effects of SLR. We are particularly interested in the team's proposed objective to evaluate how key attributes of natural and nature-based features—elevation, vegetation composition, and time since restoration—affect coastal protection related to SLR.

For over 15 years, the Bonneville Power Administration has co-led development and operation of the Columbia Estuary Ecosystem Restoration Program (CEERP), which is focused on restoring tidal wetlands in the 1500 km^2 floodplain of the tidal river and estuary. The Columbia River is tidal to river kilometer 234, at Bonneville Lock and Dam. Tidal wetlands on the Columbia and elsewhere in the Pacific Northwest provide key habitat functions for juvenile salmon, the primary goal of the CEERP, but it is recognized that other potential functions of tidal wetlands include providing natural barriers to coastal impacts such as storm surge, sequestering carbon, and buffering or storing floodwaters. Several tidal wetland restoration projects in the vicinity of the Grays River, a tributary to the Columbia, are part of the CEERP. We have previously successfully collaborated with a proposal team member, Pacific Northwest National Laboratory, on research and hydrodynamic modeling in the Grays Bay area in relation to the CEERP. Our program is interested in the results of future research and model applications to quantify co-benefits of tidal wetland restoration, increase understanding of the trajectory of restored wetland development, and improve understanding of the resilience of natural and restored wetlands to sea level rise.

The Bonneville Power Administration would benefit from this project's proposed evaluation of the likely effects of SLR on various landscape-scale designs for tidal wetland restoration and the specific ecosystem services associated with least-disturbed and restored tidal wetlands near Grays Bay, WA. The results would be useful in refining the identification and prioritization of land acquisitions by the CEERP and selecting restoration designs based on potential future resilience. We look forward using the results of this project to help us evaluate the utility of tidal wetland conservation and restoration as cost-effective, multi-beneficial strategies for improving resilience to SLR on the Columbia estuary floodplain.

Thank you for the opportunity to express our support for this important project.

Sincerely,

Jason Karnezis
Estuary Lead
Bonneville Power Administration
jpkarnezis@bpa.gov
503.230.3098

Coos Watershed Association

Coos Watershed Association
300 Central Ave.
P.O. Box 388
Coos Bay, OR 97420
Office (541) 888-5922

National Centers for Coastal Ocean Science
1305 East West Highway
Silver Spring, MD 20910

January 10th, 2019

To Whom It May Concern:

I am writing to express the Coos Watershed Association's (CoosWA) support for the Oregon State University-led team's proposal, "Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands" submitted to NOAA/NCCOS's Ecological Effects of Sea Level Rise grant program. CoosWA is very interested in supporting this research designed to help Pacific Northwest coastal decision makers evaluate whether sea level rise (SLR) itself will affect the utility of conserved and restored tidal wetlands for helping make coastal communities more resilient to the effects of SLR.

Our organization has been working to improve watershed conditions in the Coos basin for 25 years, including work in tidal wetlands. Our strategic plan has specifically identified doing more tidal wetland restoration work as a priority for our organization. We would benefit from this project's proposed evaluation of the likely effects of SLR on specific ecosystem services associated with least-disturbed and restored tidal wetlands in the Coos basin. The projects work would be directly responsive to uncertainties in the range and effects of predictions for SLR in our region. Specifically, clarity in the rate and threshold of SLR that would trigger habitat shifts that would alter ecosystem services. Our group works at the nexus of these services that include a broad range of economic, social, cultural, and ecological benefits and values derived from tidally influenced habitats. Current efforts, both in the Coos and regionally, to identify and prioritize restoration efforts and resources through an optimization model would directly benefit from a more precise understanding of spatial and temporal changes in flooding that can be expected from SLR. Carbon sequestration is a novel element yet to be considered in tidal restoration planning and development. Our group is very supportive of this proposed projects efforts to more clearly define this particular ecosystem service and incorporate it into the suite of benefits that tidal wetlands provide when prioritizing and funding restoration actions. Advancing the knowledge of just how resilient tidal wetlands are to SLR in relation to these two key targets of this project will reduce uncertainty for planners and provide new resources for the critical work of tidal restoration.

The relevance and timing of this project are both prominent. We look forward to incorporating the results of this project into optimization models currently in development in order to more fully evaluate the utility of tidal wetland conservation and restoration as cost-effective, multi-beneficial strategies for improving our communities' resilience to SLR.

Thank you for the opportunity to express our support for this important project.

Sincerely,

Haley Lutz

Haley Lutz
Executive Director
Coos Watershed Association

Oregon
Kate Brown, Governor

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January 14, 2019

National Centers for Coastal Ocean Science
1305 East West Highway
Silver Spring, MD 20910

To Whom It May Concern:

I am writing to express my enthusiastic interest and support for the Oregon State University-led team's proposal, "Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands" submitted to NOAA/NCCOS's Ecological Effects of Sea Level Rise grant program. The Oregon Coastal Management Program (OCMP) is very interested in supporting this research designed to help Pacific Northwest coastal decision makers evaluate whether sea level rise (SLR) itself will affect the utility of conserved and restored tidal wetlands for helping make coastal communities more resilient to the effects of SLR.

For over 40 years, the OCMP has worked to plan for the use and protection of estuarine resources through the implementation of estuary management plans adopted by Oregon's cities and counties. Recently there has been a significant effort by our program to update habitat information, and to provide sea level rise information for Oregon's estuaries, focused on the potential impacts to community assets (infrastructure). The proposed information from this study would nicely complement the results from our recent study, in helping us to understand the ecosystem services that may continue to be provided as water levels within our systems rise.

The OCMP would benefit from this project's proposed evaluation of the likely effects of SLR on specific ecosystem services associated with least-disturbed and restored tidal wetlands in Oregon's estuaries.

We look forward to using the results of this project to help us evaluate the utility of tidal wetland conservation and restoration as cost-effective, multi-beneficial strategies for improving our communities' resilience to SLR.

Thank you for the opportunity to express our support for this important project.

Sincerely,

Patricia L. Snow, Manager
Oregon Coastal Management Program

Oregon
Kate Brown, Governor

Department of State Lands
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National Centers for Coastal Ocean Science
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January 9, 2019

Proposal selection committee:

I am writing to express support for the Oregon State University-led collaborative proposal, "Ecohydrological impacts of sea-level rise on flood protection and blue carbon sequestration in Pacific Northwest tidal wetlands" submitted to NOAA/NCCOS's Ecological Effects of Sea Level Rise grant program. The South Slough National Estuarine Research Reserve is very interested in this research. We strongly believe it will improve Pacific Northwest coastal management decisions. This will occur through better understanding of how sea level rise itself will affect the ability of conserved and restored tidal wetlands to alter the resilience of coastal communities to sea level rise impacts.

Since 1974 the South Slough National Estuarine Research Reserve has delivered important research-based information to natural resource managers, educators, and the public. Our goal is to improve the environment and the lives of community members through applied research, education, and outreach. The proposed project is an excellent example of how scientific collaborations can help provide information that will facilitate better management decisions.

The South Slough Reserve will benefit from this project's evaluation of the likely effects of SLR on ecosystem services associated with restored tidal wetlands in Coos Bay, Oregon. The information will directly improve our management of Reserve properties and our work toward tidal wetland restoration. In addition, we will provide this information to local, regional, and national partners through local connections and our network of NOAA-partnered Reserves. We look forward using the results of this project to help us evaluate the utility of tidal wetland conservation and restoration in the context of SLR.

Sincerely,

Shon Schooler, Ph.D.
Research Coordinator
South Slough National Estuarine Research Reserve
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