Cover Page

Project Title: Coastal Wetland Restoration a Nature Based Decarbonization Multi-Benefit Climate Mitigation Solution

Lay Abstract

This cross-disciplinary research collaboration aims at advancing decarbonization by assessing carbon sequestration potential and economic value of nature-based coastal blue carbon sequestration in wetlands and identifying management and policy approaches local and regional governments can use that prioritize coastal wetland restoration and conservation projects as a viable solution for combating climate change and mitigating its impacts. Nature based solutions have recently been identified as high priority implementation targets in the USA (Biden climate-plan - helping leverage natural climate solutions by conserving 30% of America's lands and waters by 2030) and worldwide. These solutions provide multiple benefits (flood protection, jobs, food, equity, biodiversity, recreation) including climate mitigation (Griscom et al., 2017). The project will include physical, biological, economic, and social science aspects as well as field and lab work and climate ecosystem and modeling, data science, and education components. It will integrate environmental justice considerations, policy, and governance approaches to develop a framework and guidelines for incorporating coastal wetland restoration/conservation into long-term national adaptation and development plans, facilitating the inclusion of coastal wetland restoration/conservation in carbon credit markets to combat climate change while considering multiple co-benefits (e.g., developing local and regional plans, funding, permitting, leveraging science, political leadership, and community engagement). Harnessing nature-based solutions that also offer adaptation opportunities and enhance community resilience and environmental justice is key to safeguard livelihoods in the face of climate change.

Our multidisciplinary team will work collaboratively to integrate all aspects of the project, but PIs will have clear and distinct responsibilities based on their expertise. We will coordinate tasks in advance and have monthly all participants virtual meetings and annual in-person meeting. Our team includes faculty and researchers at all career stages from undergraduate students to senior scientists, providing opportunity for mentoring and professional development. A new undergraduate course focused on climate data literacy using authentic data will be developed and offered at all participating campuses.

Coastal Wetland Restoration a Nature Based Decarbonization Multi-Benefit Climate Mitigation Solution

RESEARCH ACTIVITIES AND SCHOLARLY CONTRIBUTION

Motivation:

Effective restoration and management of coastal wetlands is critical from a socioenvironmental perspective because wetland restoration can help decrease atmospheric greenhouse gas (GHG) concentrations, slow climatic and environmental change (nature-based decarbonization solution) while providing additional ecosystem services to coastal communities. Indeed, a recent report "getting to neutral" which assessed the feasibility and cost of a suite of negative emissions pathways suggested that capture and storage of as much carbon (C) as possible through better management of natural and working lands is one of most economic and effective negative emissions strategies that can help California achieve C neutrality. However, implementing wetland restoration for decarbonization is not trivial as it involves complex natural and social considerations (Figure 1). This interdisciplinary proposal seeks to provide policy and management guidelines that will maximize C sequestration in coastal wetland, while ensuring social and environmental justice and ecological sustainability (co-benefits for humans and nature). To achieve this, we will (1) delineate the natural processes and management practices within wetlands that control C dynamics, and (2) integrate environmental justice considerations, policy, and governance approaches to develop a framework and guidelines for incorporating coastal wetland restoration/conservation into local, state, and national adaptation plans. The project will assess the natural and human dynamics relevant for including coastal wetland restoration as a decarbonization solution, harnessing blue-carbon nature-based solutions that also offer adaptation opportunities and enhance community resilience and environmental justice to safeguard livelihoods in the face of climate change.

(1) Carbon Dynamics in Coastal Wetlands

Wetlands contain a disproportionate amount of the Earth's total soil C, holding 20–30% of the estimated 1,500 Pg of soil C, despite occupying only 5–8% of its land surface. Indeed, wetland soils are typically high in organic C (>20%). However, as part of the C decomposition process wetlands produce GHGs that offset soil C storage. Net C burial rates vary considerably and depend on a wide range of parameters (elevation, vegetation, inundation, salinity, etc.). **Understanding hydro-biogeochemical processes that determine net C burial rates is vital for developing wetlands restoration and management guidelines that maximize C sequestration, facilitating the inclusion of coastal wetland restoration/conservation as a nature-based decarbonization strategy.**

(2) Ecosystem Services of Coastal Wetlands

Nature-based solutions for climate mitigation, such as restoring wetlands, also provide additional benefits such as habitat for endangered species or climate adaptation benefits such as flood control. These benefits need to be modeled in conjunction with C sequestration benefits to determine the extent of complementary benefits versus trade-offs, and how a regional system of nature-based solutions can provide the highest level of joint benefits. Yet, linking the economic value of distinct ecosystem services to restoration decisions is still a significant challenge. **The economic value of C storage and other wetland ecosystem services should be included in decisions on wetland restoration to support the mainstreaming of nature-based solutions into broader adaptation efforts.**

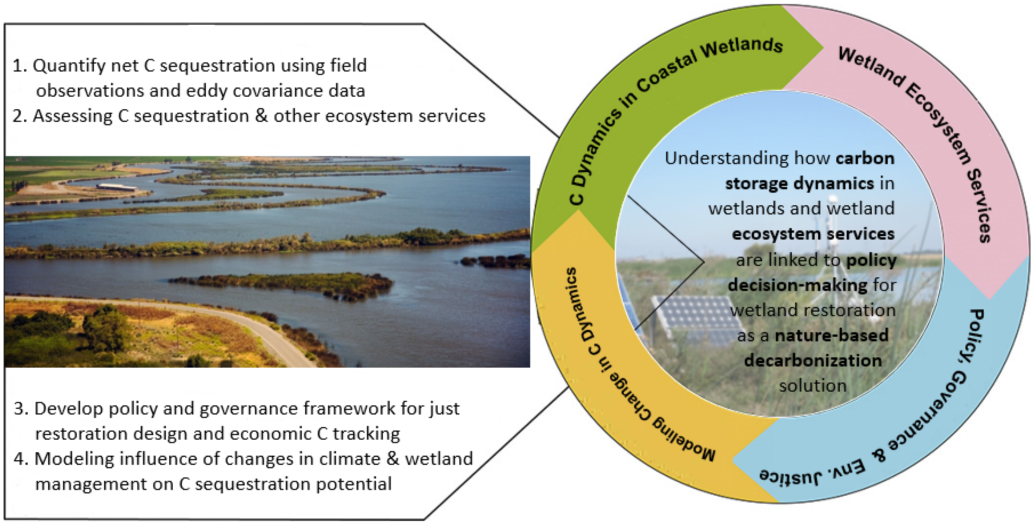
(3) Policy and Governance to Support Coastal Wetland Restoration

Implementing nature-based decarbonization solutions at the local level requires overcoming multi-scale governance challenges and regional cooperation. These challenges include developing local and regional plans, securing funding, and permitting, leveraging science and political leadership, and fostering community engagement. Overcoming these challenges requires coordinated action by local, regional, state, and national government agencies and/or jurisdictions, focused on co-producing and maintaining nature-based infrastructure that complement built infrastructure, enhances environmental equity and social justice, and provides incentives and resources for long-term resource stewardship. We need a **wetland restoration policy and governance framework that considers multiple benefits and aims to enhance social-ecological resilience and incorporate environmental justice.**

(4) Coastal Wetlands Management and Climate Change Impacts on Decarbonization Efficiency

Wetlands can be an important C sink to combat climate change and contribute to future blue C enhancement efforts and help achieve California's plans to meet the legislated goals of AB 32. However, human decisions on specific restoration practices and climate change will impact wetland C sequestration potential and associated ecosystem services. **Incorporating wetland C dynamics, restoration options and climate trends in ecosystem models will improve projections of C benefits from wetlands and their use in decarbonization plans and policies.**

Figure 1: Schematic diagram of the natural-human system research components of the project. Each color (right) and number (left) represent a unique work package (WP). All WPs inform each other resulting in a tightly coupled and integrated project.



Background

(1) Carbon Dynamics in Coastal Wetlands (UCSC, UCB, LLNL, LBL, LANL)

Wetlands are gaining increased attention for the C they store in sediments, making them valuable for nature-based approaches to decarbonization and climate change mitigation (Nellemann and Corcoran 2009, Kroeger et al., 2017). The balance between C sequestration rates in wetland soils and GHG emissions from wetlands will determine their effectiveness as net C sinks and their utility as a decarbonization strategy. California is interested in reducing, capturing, or offsetting C emissions to meet the guidelines of Assembly Bill 32 to reduce the State's 1990 C emissions by 80% by 2050. Wetland restoration can be part of the solution; however, pilot studies show that while wetland restoration can sequester C and build peat soils, CH_4 is also produced and emitted from these systems (Knox et al. 2015, Hatala et al. 2012). Our ability to confidently develop policies that focus land management efforts towards creating net C sinks in wetlands is hampered by an insufficient quantitative understanding of the biogeochemical processes controlling C dynamics (Wofsy & Harris 2002). This information is needed to optimally design restoration projects to maximize C uptake and minimize GHG emission. At present, the scientific information available to guide restoration is sparse. Knowing how fast natural wetland soils accumulate, the rate of C uptake by soils and the processes that determine this rate (Watson and Byrne 2009), as well as the magnitude of and controls on emissions of GHG from natural and restored wetlands, the optimal design criteria and management practices for restored/managed wetlands and the environmental trade-offs of such land conversion strategies are among the critical aspects to be answered for proper environmental management. **We will obtain quantitative information on below and above ground processes that control coastal wetland C dynamics and quantify net C sequestration across a range of representative wetlands. This information will be used to design best restoration and management practices that maximize decarbonization and other benefits.**

(2) Quantifying Wetland Ecosystem Services (UCSB, UCB, UCSC)

Wetlands provide multiple economic benefits to people, in terms of ecosystem services such as support for fisheries, nutrient retention, flood control, water quality improvement, tourism and recreation, and C sequestration and storage (O'Connell and Livingston 2017). The 'use values' of C storage and other ecosystem services are becoming an increasingly important argument for protecting and restoring wetlands (Martin 2017, Murray et al. 2011). However, examples of wetlands being conserved and restored specifically for decarbonization are relatively few (Crooks et al. 2010). There are significant challenges in mainstreaming ecosystem services like C storage into restoration decision-making. These challenges include (i) understanding and quantifying ecosystem services provided by wetland systems; (ii) estimating the social benefits and market values of such ecosystem services, and (iii) quantitative assessment of the potential of restoration for climate change mitigation (de Groot et al. 2010, Schaefer et al. 2015). In California, a consortium of partners provides funding for the restoration of wetlands for wildlife conservation and other co-benefits including C sequestration (CDFW 2017). Nevertheless, significant knowledge gaps related to the benefits provided need to be filled in order that restoration funds be allocated in the most effective way. **We will quantify and compare the economic values of C storage and other ecosystem services from coastal wetlands to estimate the economic benefits and social equity of benefits/tradeoffs. This information will be used to provide economic and C tracking guidelines associated with restoration projects.**

(3) Policy and Governance to Support Coastal Wetland Restoration (UCD, UCI, UCSC)

In California, wetlands are managed by a mix of private landowners and local, state, and federal agencies. Therefore, land-use management policy and decisions priorities are often driven by multiple social, economic, and ecological considerations, must navigate a complex regulatory system, include trade-offs that may be perceived as unjust, and involve entities with different capacities or willingness to implement restoration actions that shape restoration outcomes (Hagger et al 2017, Kimball et al 2015, Nielsen-Pincus et al 2015). Decisions regarding wetland restoration, such as wetland location (tidal range, elevation, land-use), size, and restoration practices (sediment infill, waterflow, vegetation), will determine the restored wetland characteristics, and subsequently the net C burial of the system. It is thus critical to understand who makes these decisions and how governance regimes can use "carrots, sticks, and sermons" (regulation, incentives, and information) to incorporate wetland restoration into long-term planning and policies. Such integration involves coordinating across jurisdictions vertically and horizontally, securing funding and permitting, leveraging science and political leadership, and fostering community engagement. We will investigate the complex social-ecological networks which situate, shape, and optimize these activities, and **develop a policy and governance framework and adaptation guidelines for decision-makers that accounts for the multiple benefits of wetland restoration, considers the capacity of different groups to implement desired restoration actions, improves environmental equity, and builds social-ecological systems resiliency.**

(4) Climate Change and Restoration Practices Impacts on Wetland C Balance (LANL, LBL, UCSC, UCB)

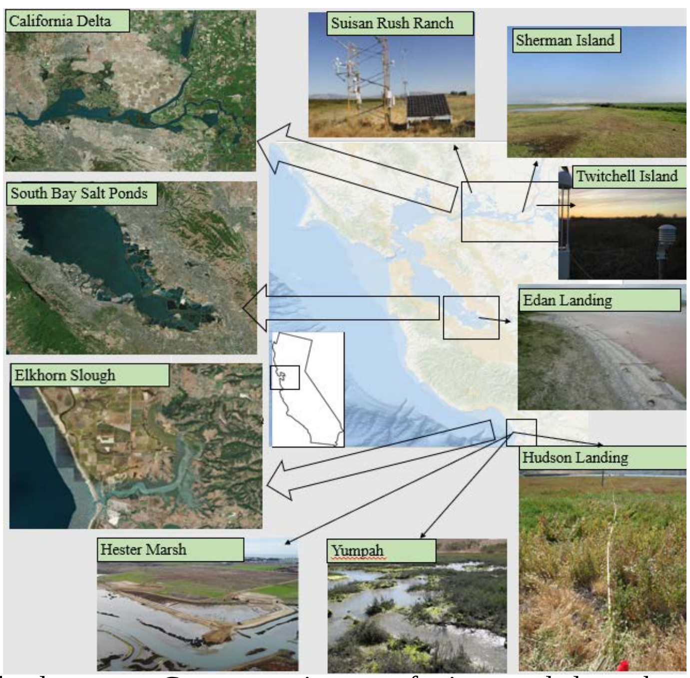
The processing of C in wetlands is now recognized as a significant component of regional and global C dynamics, however, its representation in land ecosystem models is in its infancy (TAI workshop report 2016). The ability to confidently project C and GHG dynamics is hampered by insufficient representation of integrated biogeochemical, plant, hydrological, and land use changes and processes in these models (Wofsy and Harris 2002; Xu et al., 2016). Sea-level rise and warming, related to global climate change, are also expected to impact C dynamics in wetlands. However, the exact relationship between land use change, rising sea level and temperatures, and the buildup of GHGs in the atmosphere remains uncertain (IPCC 2007). Dramatically improved prognostic capability for impacts of land use change, specifically related to restoration, and climate change and the inherent variability and granularity in these processes, is essential for the ability to project future C dynamics in coastal wetlands and hence the ability to include them in decarbonization strategies. **The LBL ecosys model (Grant et al., 2017), LANL advances in coastal processes (Zhang et al., 2021) in the Advanced Terrestrial Simulator (ATS) (Coon, et al., 2016), and biogeochemistry from ELM-PFLOTRAN will be used to investigate how different coastal wetland restoration options and climate change will impact net C sequestration potential.**

Objectives: Below we list the goals for this project and related project outcomes

(1) Obtain quantitative information on natural below ground and above ground processes that control C cycling in coastal wetlands and quantify net C sequestration across a range of representative environmental conditions. **Outcomes:** Data to improve models and inform the design of restoration and conservation guidelines that address multiple benefits including C sequestration.
(2) Quantify the economic value of C storage and other ecosystem services from coastal wetlands. **Outcomes:** economic C tracking guidelines and assessment of the value of C storage and other ecosystem services.
(3) Evaluate barriers and opportunities within current C policy and management that impact the use of wetland restoration as nature-based solution for combating climate change. **Outcomes**: a policy and governance framework that can facilitate the fair and effective design and implementation of restoration projects.
(4) Assess impacts and benefits of coastal wetland restoration practices and policy on coastal communities. **Outcomes**: adaptation guidelines and priorities that enhance community resilience and improve environmental equity, helping to safeguard livelihoods in the face of climate change.
(5) Use the ecosys and ATS models to investigate how different coastal wetland restoration options and projected climate change scenarios (sea level and temperature rise) will impact net C sequestration potential of coastal wetlands. **Outcomes:** enhancement of current ecosystem and earth system models to include coastal wetlands.
(6) Develop and teach a climate and data literacy course for UC undergraduate students and develop teaching modules for high school students and distribute relevant information materials on wetlands, C, and climate. **Outcomes** increase climate and data literacy of students and awareness of the broader community.

Work Plan: To achieve the goals discussed above we will: (1) Perform field work to measure C dynamics in diverse wetlands on multiple spatial and temporal scales; (2) Evaluate the ecosystem benefits of coastal wetlands with attention to C-offset valuation and environmental justice; (3) Analyze wetland restoration policies and governance, and their inclusion in climate mitigation; (4) Assess net C burial potential under different scenarios of land use, climate change, and restoration practices using the *ecosys* and ATS models; and (5) Use effective education and information materials to increase climate literacy and awareness. Work will take place in coastal wetlands in California where eddy covariance (EC) towers are operational, leveraging the vast amount of data available from these systems. We will measure net exchange, import, and export, of various C and GHG pools, and assess the processes and environmental parameters affecting these fluxes. Work will include ground-based biogeochemical data collection and evaluation of available and new EC-GHG emissions data, biogeochemical, hydrological, and ecosystem modeling, as well as using economic and social science tools to answer fundamental questions about opportunities and barriers for creating and implementing just policies that incorporate wetland restoration projects into climate mitigation nature-based solutions. The project will leverage and build on current studies by our team at the SF Bay-Delta and Elkhorn Slough wetlands that represent a broad range of environmental conditions, including differences in salinity, tidal range, vegetation, elevation, soil type, management practices, as well as the analytical and modeling capabilities available in the UCs and National Labs and the unique combinations of stakeholders engaged in restoration policy and governance.

Figure 2: Location of the 10 wetland EC sites to be studied in this project. Work sites include a large fraction of vulnerable communities based on education and household income data.



Sites Description: Work will take place at coastal wetlands where EC towers are installed, and data are available in the AmeriFlux database. This includes seven **Delta** sites; the Delta was home to over half of California's wetlands prior to human development. The Delta performs the critical function of water drainage, storage, and supply, provision of habitat, nutrient removal, flood protection and maintain food supplies, and nutrient cycling (O'Connell and Livingston 2017; SFEI 2015), with significant economic value (Cooper and Loomis 1991). Delta wetlands are characterized by high rates of C sequestration and net primary productivity (Zhao et al. 2009) but high CH_4 effluxes were also reported (Hatala et al., 2012). Each year, between 5 and 7.5 million tons of CO_2 continue to be released from the Delta, equivalent to 1–1.5% of California's annual GHG emissions. In contrast, simulations indicate that managed marsh of the Delta will accrete organic material at rates of ~3 cm yr^{-1} and estimates suggest that long-term C sequestration rates for impounded marshes will range from 12 to 15 metric tons C ha^{-1} yr^{-1} (Deverel et al., 2014). Restoration efforts in the Delta involve >30,000 acres and are driven primarily by two objectives - improving the reliability of water supply and protecting, restoring, and enhancing the Delta ecosystem. The Delta sites including: one historic wetland in Suisun Ranch Reserve, and six restored and managed wetlands: a restored wetland on Twitchell Island, a tulle and restored cattail wetland near Mayberry Slough on Sherman Island, a restored peatland pasture wetland on Sherman Island, a newer EC system at a disturbed site on Twitchell and a diked marsh at the northern Suisun Marsh (Hill Slough Marsh). The variety of landscapes, landcover, soil and water management approaches at these sites generates a wide range of flux densities, from soil-C-loss in some sites (+10 tC ha^{-1} yr^{-1}) to sustained C accumulation in others (-47 tC $ha^{-}1$ yr^{-1}) (Knox et al., 2015; Hemes et al, 2018). We will also include a restored salt pond in **South SF Bay -** Eden Landing, where an EC system has been operating since 2014. The South Bay Salt Pond Restoration Project will convert over 15,000 acres of former salt ponds to wetlands over a 50-year span. In 2003, 15,000 acres of the South Bay Salt Ponds were acquired from Cargill Inc., for tidal marsh restoration. The key ecosystem services in the project are provision of habitat for listed water birds, fish and other species, nature tourism, public access, and flood protection. CH_4 emissions data from a few of the extant salt ponds suggest that there are significant emissions which offset some of the C sequestration benefits. Ongoing research and monitoring studies are also examining the effects on local water quality, erosion, and flood protection (Foster-Martinez et al. 2018). Two new sites at **Elkhorn Slough** encompassing approximately 180 km^2 and contains the state's largest salt marshes south of SF Bay will be included. Recently, $3 million in funding was allocated for restoration of 61 acres of degraded marsh in Hester Marsh which will be included here (CDFW 2017).

Objectives and Methods we will use for each of the study components are briefly described below.

(1) Carbon Sequestration in Wetlands (UCSC, UCB, LLNL, LBL, LANL)

Objective: Develop wetland C budgets to shed light on processes controlling net C burial. **Methods/Approach:** Environmental parameters affecting wetland net C burial in different wetlands will be assessed using an innovative combination of field observations, laboratory analyses, and biogeochemical modeling.

C sequestration and subsurface processes – At each of the sampling sites several cores will be collected with 3 replicate cores at each sub-site (to provide sufficient material for all analyses). The pore waters and sediments in the cores will be extracted at ~1 cm resolution and analyzed for C species and a suite of relevant compounds including dissolved GHGs. We will measure soil bulk density, depth age profiles (^{210}Pb, ^{137}Cs and ^{14}C) and organic C content to calculate sediment accretion, mineral and organic matter accumulation, and C sequestration rates calculated. Pore-water will be extracted (with rhizons anaerobically), and temperature, pH, salinity, dissolved oxygen, nutrients, DOC, a suite of ions and DIC measured. Isotopes of water, tritium, DIC, SO_4^{2-} and CH_4 will be analyzed to understand water sources and flow to constrain the hydro-bio-geo-chemical models. Soil will also be analyzed for temperature, water saturation, texture, and other physical properties and the microbial biomass and diversity and activity in the soil and porewater will be assessed using microscopy, molecular techniques and stable isotope probing. Environmental parameters including vegetation type, elevation, water depth, plant biomass, age of the wetland (if restored), meteorological data and details regarding wetland management practices will be collected. A numerical vertical reaction-transport model (i.e., BeTR -Tang et al., 2018) constrained by the field observations to define C mineralization processes and rates and GHG emissions will be used. Preliminary work to test procedures indicate that the 3 replicate cores will provide sufficient material for all proposed analyses. We plan to make measurements at all the sites seasonally each year and add samples for sites/times of high GHG emissions based on EC monitoring (~75 cores over the 3 years with ~250 samples/year; not all analyses will be done on all samples).

Above ground processes, GHG fluxes to the atmosphere and lateral C transport – Measurements of CO_2 and CH_4 evasion to the atmosphere will be obtained from existing EC towers at the select wetlands. The EC method is suitable for this task, and it measures GHG fluxes directly and on a quasi-continuous basis (Baldocchi 2003). CO_2 and water vapor concentrations are measured with an open-path, non-dispersive infrared spectrometer (LI-7500a). Methane concentrations are measured with an open-path methane sensor, based on wavelength modulation spectroscopy (LI-7700). Mean wind velocity, turbulence vectors, temperature fluctuations, air temperature and humidity, energy exchange, soil temperature and moisture, water table and other quantities of the water column are also measured. Fluxes are computed and data deposited to the AmeriFlux program which will be used in innovative models (random forest and lumped parameter) to assess predictors of heightened GHG emission and upscale GHG emission estimates, respectively. Surface water chemistry will be analyzed in situ with sensors and on discrete samples, and a lateral C and other constituents transport determined as done by Richardson et al., (2020). The lateral below and above ground transport fluxes will be computed using PFLOTRAN and ATS (Ward et al., 2020).

(2) Quantifying Wetland Ecosystem Services (UCSB, UCB, UCSC)

Objective: Assess the value of C storage and other ecosystem services of coastal wetlands. **Methods/Approach:** We will use a three-pronged approach to estimate spatially explicit, region-wide values of coastal wetland ecosystem services (Crossman et al. 2013, Maes et al. 2012) and the economic value of C storage provided by wetlands and how these services benefit different stakeholder groups. We will also assess future changes to these services under multiple sea-level scenarios using the Sea Level Affecting Marshes Model (Propato et al., 2018).

Economic assessment of C Sequestration: The economic value of the damages avoided by the reductions in GHGs that restoration projects could provide, and the value gained by C sequestration will be estimated using the 'Social Cost of C' (SCC). The SCC measures the present discounted value of avoided damages from a ton of C sequestration at a given point in time. Estimates have been developed by the federal Government's Interagency Working Group, which is used by California's Air Resources Board, by Pindyck (2019) and others. The benefits from C sequestration will be evaluated alongside the economic costs of wetlands' restoration and management practices to different groups (landowners, wetland restoration specialists, wetland reserve recreational users, and state agencies). Benefits and costs will be quantified under different scenarios defined by SCC values, cost parameters, and restoration and management designs. These estimates will be evaluated in the context of California's Natural and Working Lands Inventory and California's Compliance Offset Program, which provides a potential funding source for restoration projects. Furthermore, we will investigate other possible financing mechanisms that could provide incentives for landowners to invest in wetlands restoration.

Quantifying non-C ecosystem services: We will quantify all ecosystem services using a mix of data collection and empirical modeling. We will start with direct estimates of the market value of the ecosystem services (Farber et al. 2002, Wu et al., 2001) and supplement these with indirect estimates of the supply of ecosystem services using benefit-transfer approaches (Plummer 2009) and estimates of expected values from different services using empirical relations based on land-use and biophysical indicators (Ruckelshaus et al. 2012). We will use these valuations to rank ecosystem services and assess potential tradeoffs and expected future changes to these rankings. These evaluations will be done using an ecosystem framework approach based on the principles of sustainable development with the twin goals of increasing both human and ecosystem well-being (Pascual et al. 2012). Data for the analysis is available from local, regional, and state agencies and institutions or can be compiled form empirical models that relate relevant land use and biophysical indicators to expected ecosystem. The values thus estimated for multiple ecosystem services will be synthesized, compared, and ranked to assess potential tradeoffs and synergies between C storage and other ecosystem services. We will additionally collect data on the costs of wetland restoration from restoration practitioners and agencies. These costs will be compared with the total estimated economic value of their ecosystem services, to assess the value of coastal wetlands and identify "win-win" areas where restoration can achieve multiple objectives.

(3) Policy and Governance to Support Coastal Wetland Restoration (UCD, UCI, UCSC)

Objective: develop a framework and guidelines for incorporating coastal wetland restoration/conservation into long-term local, regional, and state adaptation and development plans. **Methods/Approach:** A mixed method approached will be used to detect predictors of decision-making processes and restoration practices, and social network analysis will shed light on the networks' ability to innovate, adopt, and implement wetland restoration plans. Additionally, analyses of social variables and equity and opportunity indices will inform research questions regarding both the environmental and procedural justice aspects of C sequestration projects (approved by the IRB).

Decision-making processes - Semi-structured interviews with 5-10 stakeholders in each stakeholders' category (private landowners, local government, and non-government agencies) will be conducted to gain an in-depth understanding of perceptions of ecosystem services, wetland restoration efforts, variables that influence their decision-making about where and how to restore wetlands, and their capacity and willingness to implement desired restoration actions. Interviewees will be selected using a snowball-sampling approach and information from the interviews and literature used to develop a survey instrument. This survey will include stakeholders connected to the coastal wetland sites (from all stakeholder categories). Survey responses will be anonymous and contain mainly close-ended questions on perceptions of ecosystem services; wetland restoration practices and management capacity and priorities; and nature and extent of coordination or collaboration with other stakeholders. Socio-demographics information and mission and goals of organization will be assembled and analyzed quantitatively to detect predictors of decision-making processes and restoration practices. Social network analytics such as exponential random graph modeling will be used to evaluate how the size, composition, and types of ties within governance networks affects a networks' ability to innovate, adopt, and implement wetland restoration plans.

Access and equity analyses – Using the stakeholder survey data we will evaluate procedural justice aspects of current wetland restoration efforts. Procedural justice refers to the ability of different stakeholder groups to effectively participate in decision-making processes affecting their wellbeing. Procedural justice will be evaluated based on the presence of four criteria within wetland restoration participatory processes: accessibility (language, transportation), recognition (of the legitimacy of stakeholder groups' role), influencability (does participation materially shape outcomes), and historical justice (intentional emphasis on addressing power inequalities between participants) (Schlosberg 2007; Ottinger et al. 2014). We will also evaluate the conditions under which policymakers do (and do not) effectively consider environmental justice metrics in the planning and implementation of wetland restoration. This will suggest opportunities, and barriers to integrating environmental justice objectives into wetland restoration and inform the production of a guideline for policymakers in implementing environmental justice considerations into wetland restoration projects for C sequestration planning and implementation.

Beneficiaries from ecosystem services - Using the ecosystem service economic evaluations data we will evaluate the primary and secondary beneficiary stakeholder groups through an environmental justice lens. Using information from these analyses and secondary data from census and regional indices, we will evaluate in monetary terms, which communities are likely to benefit from both C sequestration and non-C ecosystem services. Finally, combining data from all four WPs, we will evaluate how the use of environmental justice and rights-based criteria shift prioritization and site selection within wetland restoration projects. We will compare the site selection outcomes under different conditions of value prioritization. For example, under a "maximize C sequestration" scenario, we will describe the outcomes for different values (e.g. environmental justice, carbon offset, etc.) and compare them to other scenarios such as "maximize community benefit," "maximize economic efficiency," etc.

(4) Climate Change and Restoration Practices Impacts on Wetland C Balance (LANL, LBL, UCSC, UCB)

Objective: Evaluate expected changes in C sequestration potential for different wetland restoration practices and climate change perturbations. **Methods/Approach:** The *ecosys* and ATS models will updated to include coastal wetlands and used for assessing C sequestration rates to quantify expected future changes in the C sequestration under different combinations of wetland characterization, climate change, land use, and sea levels.

Changes in C sequestration: *Ecosys* has been applied to non-coastal wetlands (Chang et al., 2019; Grant et al., 2012; Mezbahuddin et al., 2014), and has showed good performance with respect to observations but has yet to be tested for coastal wetlands and incorporate their unique processes (salinity effects and lateral C transport). We will first use observations to evaluate the current *ecosys* model predictions of GHG exchanges, C burial, and plant dynamics. We will then incorporate processes informed by the BeTR into *ecosys'* aqueous chemistry and microbial modules to improve the salinity effect on biogeochemistry, GHG exchanges and pore-water chemistry. We will explicitly represent the hydrological regime lateral C and nutrient transport and conduct gridded *ecosys* simulations to directly compare predicted GHG emissions with the EC measurements, and indirectly as functional responses. We will perform ensembles of simulations spanning realistic ranges in resolution, spatial heterogeneity of system properties and parameter values based on our analyses and the representative wetland settings (see site description).

The Advanced Terrestrial Simulator (ATS) is a fully three-dimensional parallel ecosystem modeling capability with run time control over the representation and coupling of surface and subsurface processes. It uses a flexible unstructured grid representation allowing for significant refinement in areas of interest (e.g., streams and estuaries), with coarser resolution elsewhere in the watershed. To investigate the impact of restoration practices on the C sequestration, we will develop both transect and full three-dimensional models of representative sampling sites (based on salinity, vegetation, and tides). We will leverage the advances on biogeochemistry models of the C and GHG cycles in the estuary developed in PFLOTRAN (WP 1), along with advances in *ecosys*. We will leverage the salinity transport and density dependent flow capabilities in ATS and explore the ATS coupling with the DOE FATES model to capture the impact of salinity on the salt marsh and estuarine vegetation. We will perform ensembles of simulations for scenarios of future climates that are both dryer and wetter, and with more intense precipitation events, to quantify the impact of restoration practices on future C-sequestration in the coastal zone.

(5) Integration– Each of the WP and tasks described above will inform other WPs resulting in a transdisciplinary, collaborative, integrated project. While each of the models have been carefully chosen to capture their unique, albeit critical, capability to quantify or simulate C processes in changing wetland environments, we have a specific task focused on data and model integration. This entails connecting site-specific models/sensitive parameters to coarse-scale wetland simulations in ATS. The main task here is to link site-specific reactive transport models (BeTR, PFLOTRAN, WP1) to above-ground models (i.e., ecosys WP4) that can then directly inform/compare against wetland scale watershed simulations (i.e., ATS-PFLOTRAN-FATES, WP4). At present, there is no model that can capture the entirety of above- and below-ground processes impacting C cycling in wetland environments, especially as would be expected under salinity, sea-level and other dynamic vegetation changes under future climate. This integration task will therefore provide important information regarding the impact of subsurface redox biogeochemistry on aboveground C dynamics, and feedbacks between these processes at a multitude of scales. Moreover, each of the hierarchy of models presents unique information regarding vertical, deep fluxes of C, to capturing the impact of lateral connectivity and ultimately, leading up to the wetland scale; thereby highlighting missing links and processes at each scale of investigation. To connect this to WPs 2 and 3, we will conduct a sensitivity analysis to identify ecosystem services that are the most sensitive to sea-level and temperature change scenarios. These services and sensitive parameters will then be included/adequately parameterized in ATS.

RESEARCH TEAM, INTEGRATION, COLLABORATION STRUCTURE AND MUTUAL BENEFITS

Our multidisciplinary team will work collaboratively to integrate all aspects of the project, but participants will have clear and distinct responsibilities based on their expertise (e.g., will work in teams on specific task, see Project Management Fig. 3). The project is divided into four work packages (WP, coded by color in the boxes below and in the proposal text) as well as a management & coordination (MC) and an integration, education, and dissemination (IED) WP (red boxes). Each WP includes several "tasks" (black boxes below the WP box) and each of the WP is headed by a team of one junior and one senior investigator (named in the colored boxes). Similarly, each task is headed by a lead investigator (first name in the box in bold) who will work with other investigators, students, and/or postdocs in the team to accomplish all research within the specific task. The task lead investigators will be responsible for coordinating with the heads of other tasks within the WP and for integrating with other WP. All participants for each WP (all tasks withing the WP) will have monthly WP virtual meetings. The different tasks that involve field work or work with stakeholders will coordinate the timing for data/samples collection to ensure data/samples are collected efficiently and meaningfully (at the same time). The IED teams will meet quarterly with WP leads to ensure information exchange among WPs. An annual in-person meeting (if possible) for all participants at one of the UC campuses will be coordinated to share progress, plan next steps, raise concerns and network (possibly scheduled to coincide with a scientific meeting where results will be presented). We will also have a kickoff meeting at the start of the project at UCSC. Below a short description of the project personnel participating in each WP and task is given, followed by information about project integration and mutual benefits.

Project Management and Coordination (UCSC)

Dr. Paytan (PI) will be responsible for the overall execution of the project, meeting coordination, reporting, financial aspects and any adjustments or changes that may occur and she will also participate in the research within the sub-surface C-burial task team and work on all aspects of the IED. Paytan has extensive experience in coordinating and leading multi-institution, multi-participants interdisciplinary projects including three international transdisciplinary Belmont Forum projects, an interdisciplinary NSF funded Coastal Seas project, and a UC-Laboratory Fees Research Program (2009). Paytan also leads large outreach and education programs (Geopaths, LOREX) and assumes many leadership roles in scientific societies (AGU, ASLO, Geochemical Society).

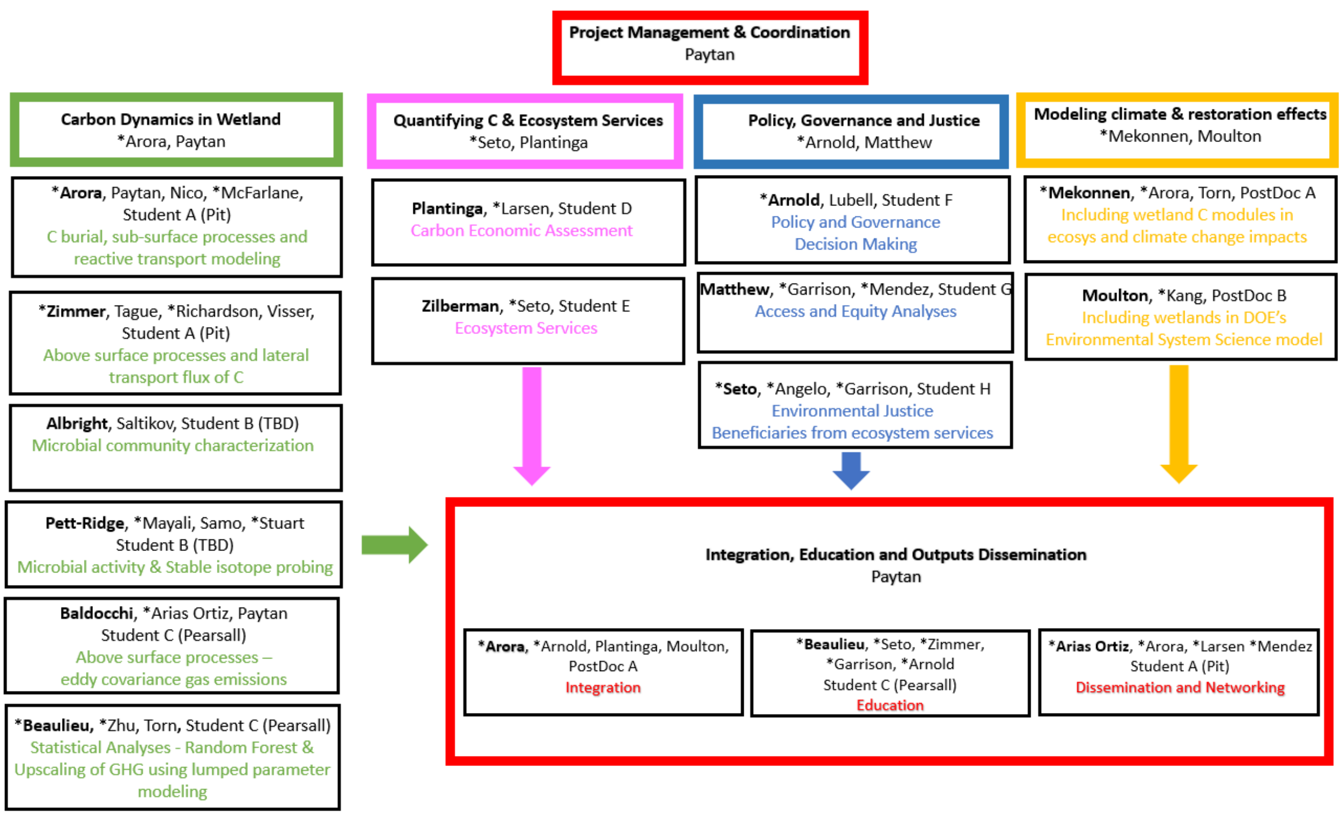


Figure 3: Diagram of work packages (WP) color boxes and tasks within each WP. The first name within each box will lead the task as described below. *Indicates early career investigator.

(1) Carbon Dynamics in Coastal Wetlands (UCSC, UCB, UCSB, LLNL, LBL, LANL)

The C sequestration and subsurface processes work will be led by Arora and Paytan. Arora's research focus is on reactive transport modeling, upscaling of hydrological and biogeochemical parameters/properties, and understanding ecosystem processes and functioning at different space-time scales and she will oversee all the modeling aspects of the WP. Paytan is a biogeochemist with extensive experience working on wetland biogeochemistry and C dynamics in wetlands and has firsthand experience with all field and analytical work of the WP. This WP include six unique tasks **(1) C burial, sub-surface processes and reactive transport modeling** – this task led by Arora and Paytan with expertise described above also includes Nico, and McFarlane who will focus on transition metal redox processes in the wetland and how metals interact with soil C stabilization, radiocarbon analyses and factors influencing the amount and longevity of C stored in soil, respectively. The field, lab and modeling work will constitute part of PhD candidate Pit (Student A) thesis project and she will be involved in all research aspects. **(2)** a**ssessing lateral transport of C and other constituents in the wetlands** - will be led by Zimmer and Tague and they will work with Richardson a postdoc in Paytan lab whose research is focused on lateral C transport in the Delta (Pit will work on lateral transport at the other sites). Visser and Rowland will conduct isotope tracing of subsurface transport and assess climate change impacts on watershed process and modeling. Collectively the team has expertise in surface water and groundwater sampling and analysis, modeling of spatially distributed C, N and water, watershed processes, and the impacts of climate change on water resources and water quality. Tasks **(3) and (4)** focus on microbial community and microbial activity rates as related to C cycling and will be led by Albright and Saltikov and Pett-Ridge respectively along with their research groups (Microbial C Cycling at LANL, Environmental Microbiology Saltikov, and Soil-Microbiome and Environmental Isotopes Systems at LLNL) and a PhD student who will be recruited for the project. These groups have all the necessary equipment and expertise (community genomic analysis and modeling, fluorescence microscopy, Chip-SIP, STXM-SIMS) to conduct this work and they will link the microbial data to the biogeochemical data obtained from the sub-surface and surface field work results and inform the ecosystem modeling task. Tasks **(5) and (6)** focus on data obtained from the EC towers and assessment and modeling of GHG emissions from the wetlands. The emission work will be led by Baldocchi and Arias Ortiz a postdoc who is working on the EC sites and Paytan who is responsible for the new EC towers at Elkhorn Slough. Zhu, Beaulieu and Torn will focus on analyzing the EC data available in the AmeriFlux database using innovative models to identify host-spots and hot-moments of heightened emissions and upscale the observations from the tower to the ecosystem scale. Tasks 5 & 6 will be part of the PhD thesis of Pearsall (Student C). The combined data from all tasks in this WP will enable calculation of net C burial in diverse wetlands and shed light on the processes and conditions determining the net burial efficiency to inform restoration practices, informing all three other WP.

(2) Quantifying Wetland Ecosystem Services (UCSB, UCB, UCSC, UCD, UCI)

WP 2 includes two tasks (1) **economic assessment of C Sequestration** which will utilize data from WP 1 on net C sequestration potential to estimates the value gained by C sequestration using the 'social cost of C' (SCC). This task will be led by Plantinga and Larsen with a PhD student at UCSB. Larsen works of landscape determinants of ecosystem services and disservices and the ecological drivers and impacts of land use transitions and Plantinga has done extensive research on the economics of C sequestration in terrestrial systems and the valuation of ecosystem services from land and how these are impacted by climate change. He also develops methods for econometrically modeling land-use decisions and of environmental policies that affect these decisions (which will inform WP 3 and incorporate scenarios form WP 4). Zilberman and Seto along with a student at UCB will focus on (2) **quantifying non-carbon ecosystem services from wetlands**. Zilberman's specific experience with agriculture economics is important for assessment of the cost and benefit of conversion of agriculture land to wetlands. The results from both the C and other ecosystem services work will inform the Environmental Justice task of WP3 (led by Seto) and information from WP4 on climate impacts will be used to see how these climate impacts affect these services.

(3) Policy and Governance to Support Coastal Wetland Restoration (UCD, UCI, UCSC)

WP 3 includes 3 tasks (1) **Policy and governance and decision-making** led by Arnold and Lubell at UCD, where they work on wetland management (among other things) with focus on analysis of the interactions among policy institutions, human behavior, and political decisions in the context of environmental and natural resource conflicts. They will be working with a PhD student to identify factors that encourage or discourage policy decision-makers from developing and implementing policies relevant to wetlands C sequestration. (2) **- Access and equity analyses** will be jointly led by Matthew, Mendez, Seto and Garrison and a PhD student at UCI. The focus here will be on assessing barriers to effective and fair community participation in decision-making and developing guidelines for facilitating procedural justice (3) - **Environmental justice (EJ)**, **beneficiaries from ecosystem services** will be led by Seto, Angelo, and Garrison and at PhD student at UCSC supported by the UCI team with the goal of identifying different implementation scenarios and assessing their impacts on wetland-affected communities from an EJ perspective. Expertise mobilized for WP3 includes coastal law and policy, political ecology, resource governance, community engagement, EJ, and bridging political economic and cultural approaches to environmental studies. WP3 strongly links with WP2 and WP4 assessing who benefits from the restoration ecosystem services and how this will change under different restoration conditions, management, and climate change scenarios.

(4) Climate Change and Restoration Practices Impacts on Wetland C Balance (LANL, LBL, UCSD, UCB)

WP4 is focused on modeling and will include (1) **refinement of the *ecosys* mode**l – led by Mekonnen, Arora, and Torn at LBNL, they all have been working with this model and are excited to include wetland processes into the model; They will mentor and supervise a postdoc (postdoc 1) that will work on the model and will also integrate the various modeling outputs to insure continuum of spatial and temporal scales under the supervision of Arora. Task (2) includes **enhancing the coastal processes in the ATS model and its coupling to the FATES model** led by Moulton at LANL and who will be working with Kang and postdoc 2. Each task will involve a post-doctoral fellow experienced with climate and/or ecosystem modeling that will work collaboratively with a UC PI and one of the lab teams. The scientists at LBNL and LANL have extensive expertise with computational ecosystem and earth system modeling as well as multiphase reactive transport modeling across scales.

Integration, Education and Dissemination

Paytan will be responsible for the integration of the outputs from the WPs and the education (see below) and dissemination of the results. For the **integration** task she will work with Arora, Arnold, Plantinga, Moulton who are leading the different WPs to ensure that the specific goals, work conducted, and results from each task are coordinated with the needs of all WPs and that these outputs are contributing best practices to facilitate nature based decarbonization via wetland restoration while considering benefits to multiple sectors under different climate conditions. Importantly, the various WP tasks relay on input from other WP hence the integration is crucial for the success of the project and will also ensure that the whole is more than the sum of the parts. For example, data from the field and lab work (WP 1) will inform the modeling (WP 4) and the modeling results will be important for calculating the C economy value and ecosystem benefits under different climate scenarios (WP 2) and designing of appropriate policy guidelines that take these into account (WP 3); the ecosystem services and C economy (WP2) will inform the environmental justice work (WP 3) and ultimately the guidelines for best management of wetland restoration to increase C decarbonization and related policy, governance and social justice implications.

Beaulieu, Seto, Zimmer, Garrison, Mendez, Arnold and Paytan will work on the **education** task which include mentoring and professional development for students directly involved in the project (graduate and undergraduates) and the development of a new upper division undergraduate course focused on climate and data literacy using authentic data which will be offered in participating campuses (see details below). Paytan has the required curricula development and science education skills, Beaulieu uses interdisciplinary approaches that implement statistical and machine learning techniques to make best use of observations and outputs from model simulations. Garrison is an expert in data visualization and GIS and Beaulieu, Seto, Zimmer, Mendez, Garrison, and Arnold all teach relevant courses and are involved in education programs in their respective departments. The team represents different departments and campuses with instruction in the environmental science area.

Arias Ortiz (leading the *Global Change Research Wetland* group at the Smithsonian), Arora (*Early Career Network-of-networks group*), Larsen and Mendez will focus on **dissemination**. They will construct an outward looking webpage for the project and social media communicating channels. In addition to publication in peer reviewed academic journals and presentation in meetings we will prepare information pamphlets for various stakeholders, animation videos, townhall presentations and showcase the project as an ESRI Story Map.

STUDENT RESEARCH TRAINING OPPORTUNITIES

Eight graduate students, four postdocs will work on the project (see Fig. 3). In addition, a new undergraduate course focused on climate and data literacy using authentic data, including data collected for this project, will be developed, and offered at all participating campuses. Internships for 5 undergraduate students will also be available with particular focus on increasing participation of underrepresented groups. At least two scientists on the project team working on different tasks will serve as mentors (academic advisors or committee members) for each of the 8 graduate students, ensuring expanded breath of research and exposure to different work and mentoring styles. All students will participate in the relevant WP meetings and the annual project meetings and workshops and either participate in the field work campaigns or visit the field sites (modelers and social scientists). Each of the graduate students will also mentor a summer undergraduate intern honing their mentoring and communication skills. Graduate student mentors will get training in aspects of mentoring and project design via professional development workshops offered quarterly. The undergraduate interns will participate in the UCSC GEOPATHS internship program to get mentoring and career preparation (https://geopaths/summer-internship-program). Providing students with the opportunity to be directly involved in a large interdisciplinary project that utilizes a wide range of methods and approaches will prepare them for the complex problems facing humanity and the environment in the 21st century. Students will present results at conference and on year 3 of the project we will convene a session on Wetlands, Carbon and Climate at the AGU meeting and all students (and other participants) will present their research results and learn from other scientists working on related issues from around the world. A dedicated Slack channel for students will be set and students will be able to post blogs on the project website and social media.

The power of data in driving better decision making, designing better programs, and delivering more effective services to citizens is well recognized. 21st Century students must develop the skills to solve the complex problems facing their generations. To address this goal, we will develop and teach a course that provides data literacy skills while addressing climate issues (including C sequestration in wetlands). The project will build on the notion that the most effective strategy for enhancing students' data literacy is through the direct use of authentic data of relevance to the students. The class well build on and adapt the LHS Climate & Data ACLIPSE activities (https://mare.lawrencehallofscience.org/curriculum/climate-data-aclipse-activities) which Paytan has helped develop and evaluate and on an NSF funded award to adapt these activities using local datasets (NSF IUSE – DIG-CAMP). The project will include two components (1) developing and testing an upper division course geared towards providing undergraduate students with tools and experiences that will increase the ability of participants to understand, evaluate, work with, analyze, model and present real data. (2) dissemination via a series of workshops to share the course content and lessons learned at other UC campuses through workshop and direct communication with relevant departments. Four of the five campuses involved in this project are already committed to offer this class. The class can also be offered virtually from UCSC to all other campuses.

CAREER DEVELOPMENT AND MENTORSHIP FOR EARLY CAREER SCIENTISTS

Our team includes faculty and researchers at all career stages from undergraduate students to senior scientists, providing opportunity for mentoring and professional development across career stages and between the UC and Labs. Each WP and task include a combination of early career and senior researchers as well as a student or postdoc providing a continuum of mentorship – undergrads mentored by graduate students who are mentored by postdocs, mentored by early career researchers who work closely with a more senior scientist. Many of the early career scientists will be leading tasks and/or WP (see Fig. 3) providing them with the opportunity to acquire leadership and management skills under the mentorship of a supportive experienced scientist. The PI Paytan will also coordinate a mentoring workshop (2 hours interactive session offered by UCSC CITL) during the first year all participants ice-breaker meeting and in following annual meeting; additional workshops focused on mentoring underrepresented groups, work-life balance, managing a research group, etc. will be offered. Paytan has extensive experience with offering such workshops as she has been doing this as part of her leadership role at AGU and the GS. Paytan will involve the early career scientists with the education and outreach activities as well (as a lead PI on two GEOPATHS projects and with a MS degree in education she has the needed expertise). Overall, participating in this large interdisciplinary project will also provide early career scientists with training and experience in project management and coordination. An early career Slack channel for networking and communication will be created.

TIMEFRAME, MILESTONES, AND EVALUATION METRICS

At the commencement of the project a kickoff and planning meeting will take place where project PI and WP leads will present to the rest of the group their goals, tools, and work plans. At that meeting the suggested communication and field work schedules will be shared and mentoring training will be provided. As noted above monthly WP meetings and quarterly WP lead meetings will ensure continues communication and exchange and annual all participant meeting and conference participation will be included. The project website will be developed within the first month and students/postdoc recruitment initiated as needed. Annual reports will be prepared and submitted on time. Below general timelines for each of the WP and associated tasks are provided.

(1) Carbon Dynamics in Coastal Wetlands – Task 1: In spring 2022 sampling sites will be selected and student will learn the needed field and laboratory procedures as needed. In the summer and winter of each year samples will be collected at the various field sites for all proposed analyses and sediment and pore water collected from the cores. In the Fall and Spring following the field work samples will be analyzed (at UCSC and the labs) and data interpreted. In the first year the student will also start learning to work with the vertical sub-surface reaction transport model (BeTR) and in subsequent years field data will be modeled to assess C dynamics. Task 2: Surface water will be collected during the field work excursions and analyzed along with the sub-surface samples. The student and postdoc will apply the PFLOTRAN model using data collected at the field sites and the C loss via lateral exchange will be determined. Tasks 3 & 4: Student B will take part in the field work as for tasks 1 and 2 and collect and preserve samples for microbiological work. The student will spend time as needed at LLNL to assess microbial activity and link the data to the results from Tasks 1 and 2 and in the Summer spend time at LANL to characterize the community structure. Tasks 5 & 6: In year 1 The student will learn how to download and process the data to identify hot-spots and hot moments and in years 2 and 3 construct the RF and lumped isotope models to identify drivers for heightened emissions and upscale flux estimates. At the end of the project all the data needed to determine net C sequestration and driving mechanisms will be available and restoration guidelines ready.
(2) Ecosystem Services – The first 6 month will be focused on mapping the ecosystems at each site and grouping the sites based on similar characteristics. A through literature review on economic valuations of various ecosystem services will be conducted. Student D (C-economics) will evaluate and select a model (e.g., DICE) and compile a list of the ecosystem services and their value and the 'social cost of C' for the systems. In year two the focus will be on determining how these services benefit different stakeholder groups. Using information from the analyses and potential secondary data (local census data, relative disadvantage, and opportunity indices), what communities benefit from both C Sequestration and non-C ecosystem services in monetary terms as well as considering rights-based and access-based criteria will be assessed (in collaboration with WP 3). Finally changes valuation based on different climate change and management scenarios from WP 1 and WP 4 will be determined in year 3.
(3) Policy, Governance and Social Justice - In year 1 we will identify and interview stakeholders about perceptions of ecosystem service and wetland restoration and relevant decision-making priorities. Interview data will inform the development of a survey instrument by the end of year 1; the survey will be deployed to a broad range of coastal wetland stakeholders in year 2. The survey will collect quantitative data on nature and extent of collaboration among stakeholders and environmental justice dimensions of restoration efforts, By the end of year 2, statistical and social network analyses of the survey data, using multivariate regression and exponential random graph modeling will be done to detect predictors of just and equitable restoration decision-making. Year 3 will be devoted to completing analyses, preparing and submitting manuscripts and outreach that delivers practice-oriented, actionable insights.
(4) Modeling – Postdocs with modeling experience will be recruited as soon as the project starts. The first year will be dedicated to developing/using the wetland module in ecosys to quantify C dynamics at representative wetland sites. Working in conjunction with Student A, further links between ecosys and reaction transport models will be developed to capture the entirety of above and below ground processes. Years 1 and 2 will focus on validating and calibrating the model to capture field dynamics. Year 3 will focus on testing the results of the combined model under climate perturbations. In parallel, simulations in ATS will commence in Year 2 building off the PFLOTRAN. Year 3 will focus on capitalizing on information from ecosystem services team and sensitivity analysis results to further include/analyze these parameters and their impact on coastal wetland dynamics at a larger footprint scale.
Evaluation Metrics - Project deliverables include: (1) extensive biogeochemical data relevant to processes controlling C dynamics and GHG emissions that will be incorporated into reaction transport and C mass balance models and used to develop a framework for wetland reconstruction and monitoring; (2) quantification of ecosystem services and economic benefits from such projects; (3) white paper targeted at policy decision-makers that describes the benefits and drawbacks communities may experience by employing wetlands for C sequestration, the situations in which this approach is most useful or viable, ways to make this politically and logistically tractable, and best policy practices; (4) expansion of the *ecosys* and ATS models to include process-based C dynamics in coastal wetland; and (5) new collaborations established, early career and student training, multiple publications and communication materials and a new course for undergraduate students. Ultimately, **we will use this information to construct a set of recommendation that will enable wetland restoration projects to consider C sequestration in their design/management**. Our data will also provide insights into how fluxes may change in the future because of climate change, informing restoration planning and their value in C markets and contributing to California's GHG emissions reduction goals and Global Warming Solution Act AB 32 (Deverel et al., 2017).

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