I. Background

Climate change is significantly influencing how ecological restorations are planned, especially at interfaces of aquatic and terrestrial systems, such as salt marshes. This planning process has grown to encompass not only the historic ecology of a system, but also its resilience to increasing environmental extremes, *e.g.,* sea level rise, as well as potential emerging funding mechanisms, such as carbon sequestration markets. The complex interactions between hydrology and carbon biogeochemistry in salt marshes present an added challenge in restoring these dynamic ecosystems while mitigating multiple impacts of climate change.

The Herring River Estuary (HRE) is a small watershed within the Cape Cod National Seashore (Fig. 1). The river extends 5 miles from Wellfleet Harbor to its headwater kettle ponds. Its historical salt marshes once covered ~900 acres of intertidal land. Through a series of diking and marsh drainage projects in the estuary, including the construction of Chequessett Neck Road dike in 1909, tidal flow to the HRE has been severely limited for over a century. Until a recent storm-induced breach, flows between Cape Cod Bay and the HRE have been restricted through a six-foot wide fixed opening in the dike. This disconnection has widely impacted the ecology of the HRE, decimating its eponymous Herring Run, allowing invasive marsh grasses, *e.g., Phragmites australis*, to become established over large areas, negatively impacting water quality through eutrophication and biogeochemical weathering of dried sediments.

The National Park Service (NPS), with research support from the United States Geological Survey (USGS), has spent decades planning the tidal reconnection of the HRE, which is complicated by the subsidence of salt marshes upstream of the dike by up to one meter.[1] If NPS were to simply remove the dike, high tides would drown the remaining marshes, turning the estuary into mudflats and open water. This subsidence of a restricted salt marsh presents a microcosm of sea level rise's impact on tidal marshes globally, which must continue accreting sediment to raise their surface elevations if they are to remain above water. It is the design hypothesis of NPS and USGS that if tides are gradually reintroduced to the HRE, suspended sediments will settle atop existing marshes, slowly rebuilding their elevation to pre-dike levels, which still exist outside the dike-impacted areas. NPS has developed a plan to replace Chequessett Neck Road dike with an adjustable tide control structure, which can be operated to limit tidal influx to set elevations while allowing much larger volumes of water to enter and exit the estuary each day.

After decades of planning, reconstruction of the dike is finally slated to begin towards the end of this year. Our proposed project is ideally timed to span the before and after periods of the reconstruction of this bridge and installation of the new adjustable tide control structure. Upon completion, small incremental increases in upstream water level will be initiated over a one-year period to the new target height, followed by two years of observing the impacts of tidal reintroduction. We propose to measure water velocities and methane fluxes before, during, and after tidal reintroduction, presenting a unique opportunity to provide critical information to both guide and evaluate this complex restoration project, and increase the potential for impact more broadly as we look to make our coastlines more resilient to climate change induced sea level rise.

A major challenge to planning the operation of this tidal control structure is accurately understanding the complex hydrodynamics of the system. USGS has conducted detailed acoustic bathymetry surveys of the HRE near the dike, but the abrupt restriction of the channel through the dike orifice makes it impossible to derive an accurate flow rate from this bathymetry with current USGS methods. This data gap has made it impossible to validate the hydrodynamic model of the HRE, which is necessary to extrapolate water level, salinity, and nutrient targets under current and restored conditions, with broad implications for the system's hydrodynamics and biogeochemistry.

We propose to measure flow rates during the days centered on some of the highest annual tides, both before and after dike reconstruction, using a remote sensing technique developed by the PI's group - infrared quantitative imaging velocimetry (IR-QIV). This technique relies on sensitive infrared cameras to remotely track subtle temperature patterns that naturally occur on surface water flows. By tracking these patterns across successive images, which are georectified, IR-QIV can derive instantaneous velocities for thousands of sub-areas within an image of the water surface.[2] By combining these velocity measurements with USGS' bathymetry dataset, an objective is to establish a rating curve of flow through the dike at different tide heights and gate configurations for hydrodynamic model calibration and validation, which will directly inform the operation of the new tidal control structure as the HRE is restored to an unrestricted tidal regime.

Our research team is comprised of scientists from the USGS, NPS and the Center for Coastal Studies (CCS) with decades of modeling and field monitoring experience in the HRE, as well as faculty in Civil & Environmental Engineering (CEE) and Ecology & Evolutionary Biology (EEB) with wide-ranging expertise on hydrodynamic and biogeochemistry field research and data analysis methods. We have two principal objectives: (1) Deploy our novel infrared-based surface velocity measurement tool at the HRE dike and at one location up-estuary in a manner that allows us to look in the up and down flow directions under both ebb and flood tides. This data set will be used to: (i) validate existing hydrodynamic models of the HRE filling a critical need and gap in the restoration project, (ii) monitor air-water gas transfer as a function of tidal phase, and (iii) monitor bathymetry changes over the duration of the deployment due to sediment accretion and erosion. (2) Address significant gaps in the knowledge of carbon cycling in the HRE by applying our infrared remote sensing tools to measure lateral and methane fluxes in the estuary – quantifying several biogeochemical processes of great importance for the restored HRE to act as a carbon-sequestering ecosystem, and ultimately informing the direction of this restoration project.

II. Intellectual Merit

The planned reintroduction of tidal flows to the HRE requires detailed knowledge of the sediment transport potential of flows as a function of tidal elevation. To date NPS and USGS have

Figure 1: Lower HRE, with potential areas of lateral flux observation circled red.

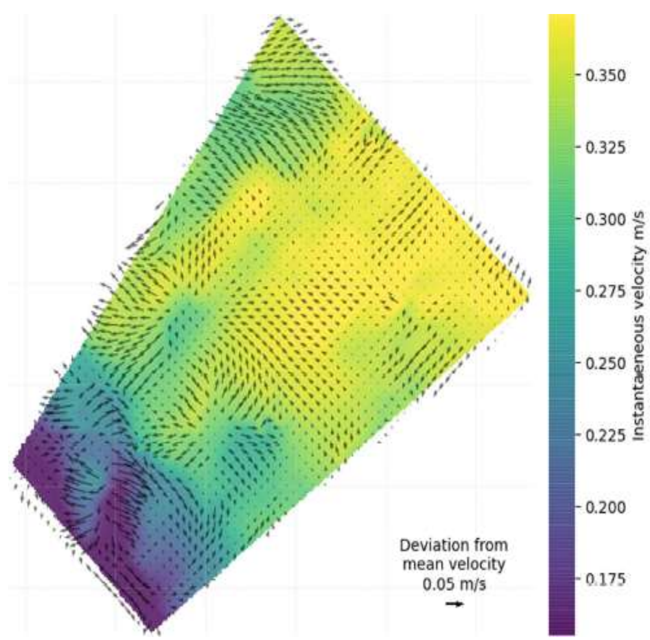

Figure 2: IR-QIV measured instantaneous velocity field. Vectors are deviation from the mean[2].

relied on unvalidated and unverified hydrodynamic models to plan this reintroduction. However, sediment transport processes are highly sensitive to the actual mean and turbulent flow velocities. Modeling flows in the HRE is extremely challenging due to the complex relationship between flow and drag forces through the salt marsh vegetation and over the complex bedforms that result from the highly dynamic flows through the primary and secondary channels. The IR-QIV measurement technique can measure at high temporal (> 1 Hz) and spatial (< 10 cm) resolution in time and space over large spatial areas (order 100 to 10,000 m^2). Using well established approaches for extrapolating the surface velocity to channel flow rate[3] we will develop the 10-minute mean surface velocity and channel flow rate over multiple tidal periods centered on the spring tide, the maximum tidal excursion in the primary 14-day tidal range period, allowing for both the validation and verification of the NPS/USGS hydrodynamic models. This will significantly improve the predictive ability of these models to capture the erosion and accretion processes, and markedly increase the project's probability of success.

Wetlands are the largest natural source of atmospheric methane at about 30% of total global emissions.[4] Salt marshes and sea grass beds constitute important sinks of *blue carbon* sequestered in coastal biomass. However, the mechanisms determining which coastal wetlands function as methane sinks or sources remain inadequately understood. Our implementation of infrared remote sensing at the hydrodynamic-biogeochemistry interface enables us to characterize the four largest unknown carbon fluxes in the HRE: lateral flux, ebullition (bubbling), benthic oxidation, and aerenchymous (plant) transport. Investigating these four processes using our infrared imaging methods will fill knowledge gaps in USGS's methane modeling efforts in the HRE and broadly in the science of resilient wetland restoration and greenhouse gas budgets and biogeochemistry.

We will quantify aquatic fluxes of carbon to the ocean and atmosphere. Image-based velocimetry techniques are effective in vegetated low-flow conditions[5] and can be used to measure the lateral fluxes between plant canopy and channel flows – a dominant pathway for carbon fixation/depletion in salt marsh ecosystems into the global carbon cycle.[6, 7] Wave height will be measured along the marsh periphery to infer the wave-induced contributions to lateral fluxes.

Ebullition, or direct bubbling, of methane has been observed in the HRE and is hypothesized to be a significant carbon flux. Our infrared camera can directly quantify ebullition and image methane. We will develop an image processing tool that quantifies the rate and size of methane bubbles. Methane ebullition rates can then be correlated with USGS flux tower concentration data across the HRE, increasing the accuracy of estimates of methane evasion from coastal waters. To our knowledge, there is no data available on ebullition bubble diameter and frequency – this would be a significant contribution to understanding natural methane budgets

Imaging the water surface at both the tidal flow structure and lateral flux zones (Fig. 1) will yield observations of surface turbulence, which can be used to estimate the gas transfer velocity for various carbon compounds,[8] which vary significantly across the HRE presenting modeling challenges. These same images can be used to monitor bed stress[9], or hydraulic shear, along the bottom of the estuary that affects sediment transport and benthic oxidation of methane entering the water column, which alters the carbon isotope ratio in CH_4 allowing a direct estimate of methane oxidation to CO_2 – a much less potent greenhouse gas. Comparing these measurements with carbon isotope ratios[10] from methane sampling in the HRE will help to close a critical gap in our understanding of methane oxidation in the estuary's sediments. Aerenchymous transport is another methane flux of interest, which provides a pathway for methane produced in marsh sediments to the atmosphere by passing through air channels in plants. This process may be observable in our infrared images, providing potentially four separate sources of carbon flux and biogeochemical data from a single remote sensing vantage point. Investigating these links between hydrodynamics and biogeochemistry will provide essential data for coupling the hydrodynamic and carbon models of the HRE and steering the restoration of this ecosystem toward its maximum carbon sequestration potential.

III. Impact

We will directly contribute to the successful restoration of a unique ecosystem in one of the most visited national parks in the US[11], helping this vital public resource become more resilient to sea level rise and sequester significant amounts of carbon. Relying primarily on an infrared camera for remote data collection, this proposal presents a unique opportunity for hydrodynamic measurements before, during and after a high-profile ~$50 million federal restoration and infrastructure project.[12] The proposed iterative approach to attenuating tidal restoration conditions based on calibrated flowrate data during the restoration process will set a scalable new standard for controlled coastal restorations around the world. The HRE restoration has attracted significant attention from NPS nationally, and this high-profile project presents an excellent opportunity to showcase unique measurement technologies and iterative restoration methods to federal agencies. Our project results have the potential to impact global federal agencies, as well as the non-profit and for-profit entities that work in coastal resilience and restoration.

Wellfleet Harbor, the receiving waters of the HRE, is home to a world-class oyster fishery. There is concern about negative impacts to harbor water quality due to mobilization of previously trapped pollutants from the restored HRE. The flow rating curves derived from this project will be combined with existing USGS loading rates for various nutrients and contaminants in the HRE to determine safe flow rates out of the HRE to protect the fishery, presenting a direct benefit to this rural economy. The reestablishment of favorable nursery conditions in the HRE constitutes another positive impact on regional biodiversity and commercial and recreational fisheries.

IV. Collaborations

The restoration of the HRE is an important part of protecting this ecosystem from the impacts of climate change. Massachusetts has already experienced up to eight inches of sea level rise since 1921, and the rate of this rise is increasing faster than the global rate.[13] This proposal presents a starting point for a long-term collaboration between Cornell researchers, USGS Woods Hole Coastal & Marine Science Center, NPS, and the CCS to pilot innovative measurements of transport processes and carbon sources and sinks while increasing the chances of success for a significant and highly visible federal restoration project. This is internally a new collaboration (Cowen and Sparks have never before collaborated) and importantly connects Cornell researchers to the long-term HRE restoration project – an important opportunity that could grow and broaden.

V. Interdisciplinary Research

Our collaboration between engineering and ecology presents multiple opportunities for disciplinary cross-pollination – instead of just providing hydrodynamic data to be incorporated into ecological analysis, we will look at the HRE's complex issues from multiple perspectives, as fluid dynamics and biogeochemistry influence one another during this restoration. Changes in flow rate and salinity will change marsh plant communities, which in turn will change hydrodynamics through previously or newly vegetated areas. Tidal exchange rates and lateral fluxes will influence nutrient and carbon cycling rates, which will inform the operation of the tidal control structure in a recursive way. Carbon transport processes are mediated by the fluid dynamics and marsh plants.

Beyond Cowen and Sparks co-advising graduate students, the most significant product of this proposal will be a new partnership between Cornell and two Federal agencies working to enhance coastal climate resilience and we intend to pursue long-term funding. We have identified specific opportunities at the National Institutes for Water Resources and the new NSF Civic Innovation Challenge (CIVIC) in addition to more traditional opportunities at NSF and USGS. Our partnership also provides a path to transition emerging technologies, such as IR-QIV and infrared ambient methane detection, into wider adoption for direct application by federal research agencies, better serving their climate adaptation objectives while moving the science forward.

VI. Metrics

Our measurement campaign involves deploying the camera at two principal locations: the tidal flow structure and an up-estuary location with emergent vegetation, ebullition, and salt marsh-channel transport (Fig. 2). We will occupy each location during three field campaigns. Our first objective is to develop a rating curve of flowrate vs tidal height at the newly constructed adjustable tidal structure. To maximize the range of tidal heights measured, we target spring tides during the summer fieldwork season, which will provide nearly 14 vertical feet of differential tidal flow into and out of the dike. Over the 24-month AVF project, these tides are as follows:

- July 15, 2022: 12.5’ (-1.4’ following low tide)
- August 3, 2023: 12.4’ (-1.4’ following low tide)
- June 5, 2024: 12.0’ (-0.9’ following low tide)

All three of these tides occur overnight, making these events impossible to measure with conventional visible light remote sensing techniques. However, since infrared cameras measure thermal radiation instead of visible light, daylight is not necessary to take accurate velocity measurements with IR-QIV – night often provides optimal thermal imaging conditions. We will target a preliminary rating curve by October 1, 2022, while simultaneously supporting the calibration and validation of the USGS/NPS hydrodynamic models to ensure operational planning prior to the commencement of construction is as accurate as possible. During the remainder of year 1, we will develop an image processing tool that quantifies the rate and size of methane bubbles and apply this to the ebullition images. Simultaneously we will work on linking aerenchymous transport direct measurements with infrared imaging. In year 2 we will refine our rating curve and turn our focus to lateral transport and bed stress measurements, which connects to benthic oxidation and sediment transport.

The HRE is an important research site for the carbon sequestration potential of restored coastal landscapes. A 2019 blue carbon feasibility study showed that restricted coastal wetlands such as the HRE are significant sources of methane emission, and that restoring the HRE’s 900 acres of former salt marsh could generate enough greenhouse gas offsets to pay for the entire restoration and yield nearly $4 million in additional revenue.[14] A major goal in year 2 is to use year 1 data to understand the HRE’s carbon emissions in its degraded state and how the tidal and vegetation community restoration should proceed for maximum carbon sequestration benefits. Our activities significantly advance this understanding through helping to parameterize carbon models for the HRE. This project directly contributes to the successful restoration of the HRE to maximize carbon sequestration, which could total >300,000 metric tons of CO_2 over 40 years.[12]

Furthermore, the HRE Feasibility Study was organized by the National Estuarine Research Reserve System Science Collaborative as a scalable framework for financing coastal restoration projects by monetizing the carbon sequestration benefits they provide in long-term carbon markets. Our collaboration will be an important part of scaling this restoration model to other sites in New England, the Mid-Atlantic and beyond, demonstrating the utility of remote sensing infrared measurement techniques to measure global carbon budgets at the interface of terrestrial and marine ecosystems, and connecting Cornell to this potentially impactful restoration financing framework.

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