RESTORE ACT CENTER OF EXCELLENCE FOR LOUISIANA FINAL TECHNICAL REPORT

Due within 30 days of the close of the award

Project Title: Projecting 50 Years of Relative Sea-Level Rise in Coastal Louisiana

Principal Investigator:	**Torbjörn Törnqvist**
Principal Investigator Institution:	**Tulane University**
Co-Principal Investigator:	**Sönke Dangendorf**
Co-Principal Investigator Institution:	**Tulane University**
Co-Principal Investigator:	**Anjali Fernandes**
Co-Principal Investigator Institution:	**Denison University**
Co-Principal Investigator:	**Philip Minderhoud**
Co-Principal Investigator Institution:	**Wageningen University**

A. TECHNICAL ACTIVITIES

1. **Research Summary**: Please include methods, main findings and conclusions, significance of the research, and any representative tables or figures. Approximately 5 pages**.**

Introduction

Sea-level rise and its threat to low-elevation coastal zones rank among the most severe consequences of climate change due to its expected role in driving human migration (Hauer et al. 2020), along with its detrimental impact on coastal ecosystems that rank among the most valuable on the planet (Costanza et al. 2014). While the magnitude and rate of future sea-level rise are not precisely known, it is one of the most predictable elements of the climate system and is committed to rising for at least several centuries (Clark et al. 2016, Levermann et al. 2013), owing to the slow response time of the cryosphere-ocean system.

Assessments of the future impact of sea-level rise on coastal ecosystems have significantly increased in number over the past decade (Oppenheimer et al. 2019) and include a variety of model studies (Kirwan et al. 2010, Lovelock et al. 2015, Spencer et al. 2016, Mariotti 2020) as well as the examination of past analogs of future sea-level rise, notably from the last deglaciation (Saintilan et al. 2023). While these approaches have offered valuable insights, they also come with inherent limitations. Analogs from the geologic past concern pristine coastal settings that were likely much more resilient to environmental change than the heavily human-perturbed coastal zones that dominate the Earth's shorelines today. In other words, studies of such analogs tend to result in overly optimistic estimates of their vulnerability (S. Cooley et al. 2022). Meanwhile, models must be calibrated and validated against known conditions, but projections for the future involve conditions for which observations generally do not exist. While model validation by means of the geologic record can increase confidence (as is commonly done with climate models) this also concerns conditions with little if any anthropogenic influence. Therefore, even if the trajectory of climate change were to be precisely known, considerable uncertainties remain about its impacts on ecosystems that have suffered degradation due to human activity.

In this project, we investigated the impact of the exceptionally high rates of geocentric sea-level (GSL) rise (>10 mm yr^{-1}) that have affected the US Gulf Coast since about 2010 (Dangendorf et al. 2023, Yin 2023). As shown by these recent studies, this is likely a transient phenomenon caused by multidecadal, cyclic sea-level variability associated with ocean dynamics superimposed on the climate-driven acceleration that is seen worldwide. Thus, it is unlikely that these high rates will persist in the next few decades (Dangendorf et al. 2023). Nevertheless, this period can serve as an analog for the persistent rates of climate-driven sea-level rise that are expected later during this century and beyond. We therefore view this as a full-scale experiment of the response of an iconic ecosystem to future climate forcing. We examined the impact of about 13 years of rapid GSL rise on coastal wetlands that have additionally been experiencing subsidence rates averaging ~10 mm yr^{-1} (Jankowski, Törnqvist and Fernandes 2017), along with human-caused degradation. This approach enables us, for the first time, to address the question of whether coastal wetlands can adjust vertically by increased plant productivity and sedimentation (Morris et al. 2002), a feedback mechanism often cited to enhance wetland resilience (Kirwan et al. 2016a). We believe that the analysis presented herein opens a window to the future in a way that has to date not been possible.

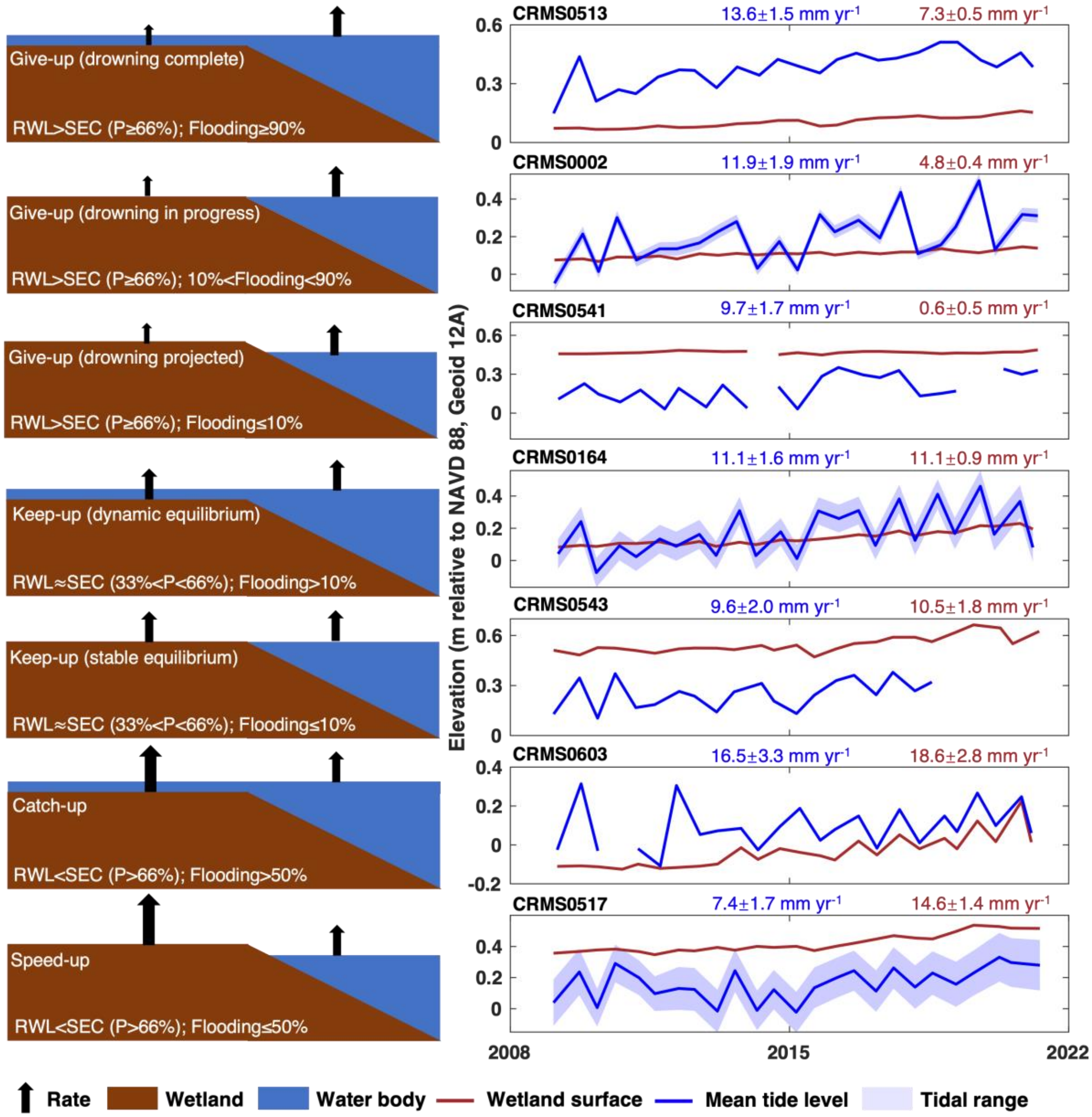

Figure 1. Possible wetland responses by means of rates of surface-elevation change (SEC) to relative water-level (RWL) change. P represents the probability of the specified RWL-SEC relationship. Characteristic examples from individual monitoring sites are shown on the right with the rate (and one standard deviation) of RWL change and SEC.

Methods

We first used reprocessed satellite altimetry data (Cazenave et al. 2022) to validate the rapid GSL rise rate along the Gulf Coast, which was derived from the tide gauges (Dangendorf et al. 2023). Then, we examined how the accelerated GSL rise in the Gulf has propagated into Louisiana's coastal wetlands by analyzing the relative water-level (RWL) data from the Coastwide Reference Monitoring System (CRMS) water-level gauges.

Next, we used the data from CRMS rod surface-elevation tables (RSET) to track how wetland surface elevation changed (SEC) and compared it with the local RWL variations during the same period. Based on the differences between the rate of wetland surface elevation changes and nearby RWL rise rates, and the differences between the elevations of the wetland surface and nearby water surface, we classified the wetland responses into two groups ("safe" and "unsafe") with 7 subgroups. With this classification scheme, the full spectrum of possible wetland responses to RWL change is captured (Figure 1). The give-up categories reveal that the wetland is unable to keep pace with RWL rise (i.e., there is a surface-elevation deficit), with the elevation comparison between the wetland and water surface determining whether drowning currently occurs. On the other hand, the keep-up categories suggest that the wetland keeps pace with the RWL rise, at least for the time interval under consideration. The catch-up category demonstrates that the wetland is gaining elevation despite frequent flooding, and the speed-up category indicates that the wetland is gaining elevation under subaerial conditions. Because tides play an important role in examining wetland flooding, we compare the monthly low tide level, mean tide level, and high tide level with the elevation of the wetland surface in the month when SEC data were collected.

Finally, we took advantage of the global sea-level projections (G. Garner et al. 2021) from the latest Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2021), from which we extracted the projected GSL rates along the Gulf Coast under different climate scenarios from 2020 to 2100.

Main findings

The GSL changes at the Grand Isle tide gauge and mean GSL changes from satellite altimetry are highly correlated ($r=0.8$, $p<0.001$), both of which showing over 10 mm yr^{-1} GSL rise from 2009 to 2019. We next assessed RWL changes within the Louisiana coastal wetlands by analyzing data from water-level gauges at 325 CRMS sites from 2009 to 2021. The median rate of RWL rise was 15.7 mm yr^{-1} (mean: 16.7 ± 7.0 mm yr^{-1}), whereas the GSL rise at the Grand Isle tide gauge was 10.5 mm yr^{-1} over the same period. This difference is because the water-level gauges also capture a significant portion of subsidence. For example, the high rates of RWL rise in the Birdfoot delta (~30 mm yr^{-1}) are due to compaction within the ~100-m-thick Holocene sediment column in this area (Heinrich et al. 2015). Rapid RWL rise is also found in an impounded portion of the Chenier Plain which is heavily impacted by manmade water control structures (Hiatt et al. 2019). RWL changes across the Louisiana coast show that 97.2% of sites exhibit a statistically significant correlation ($p<0.001$) with GSL change at the Grand Isle tide gauge, with a median correlation coefficient of 0.74. A higher correlation is observed closest to the coast in the Mississippi Delta, suggesting a decreasing ocean influence farther inland. In summary, GSL rise is the main factor that driving similar magnitudes of RWL rise in coastal Louisiana.

With the help of the unique setting of each CRMS site, on average the RSET located only 93 m from the associated water-level gauge. This allows us to evaluate the wetland surface dynamics with respect to the nearby water-level variations. By applying the aforementioned classification schemes to the 253 CRMS sites, we find that 87% of the CRMS sites fall in the give-up categories, 5% in the keep-up categories, and the remaining 8% in the catch-up or speed-up categories. Thus, only 13% constitute what we refer to here as "safe" sites. Give-up sites are widely distributed across coastal Louisiana with the most vulnerable ones (drowning complete or in progress) clustering in the Chenier Plain and inland portions of the Mississippi Delta. In contrast, most "safe" sites can be found relatively close to the shoreline in the Mississippi Delta.

We also evaluated the factors that influence coastal wetland resilience. The impact of sea-level rise on coastal wetlands is complex and varies depending on local conditions and human activities (Kelleway et al. 2017). Model studies have suggested that coastal marshes can keep up with rates of RSL rise >12 mm yr^{-1} (Morris et al. 2002) or even several times higher under favorable environmental conditions (Kirwan et al. 2010). This has led to the perception that the vulnerability of marshes may have been overestimated (Kirwan et al. 2016a). In contrast, analyses based on the paleorecord and contemporary *in situ* surveys have indicated that coastal wetlands are very unlikely to survive when the RSL rise rate exceeds 7 mm^{-1} (Saintilan et al. 2023), i.e., considerably lower than the GSL rise rate along the Louisiana coast over the past decade.

Our analysis focuses entirely on the ability of coastal wetlands to adjust vertically to RSL rise. It is well established (Brinson, Christian and Blum 1995) that these ecosystems can also retreat landward, and some studies have argued that this could result in net areal growth even under pessimistic climate scenarios (Schuerch et al. 2018). However, this neglects the fact that under such scenarios wetlands still must cope with the vertical dimension of rapid RSL rise. In addition, although salt marshes can migrate landward at the expense of freshwater wetlands, freshwater wetlands often cannot migrate into uplands due to the presence of topographic barriers (Osland et al. 2022). Hence, landward migration of coastal wetlands cannot compensate for seaward losses. Coupled modeling of marsh-edge erosion and upland marsh retreat (Kirwan et al. 2016b) demonstrates how their interplay dictates wetland extent as a function of RSL rise, sediment availability, and the upland slope. While this model study suggested that wetlands can expand under a variety of boundary conditions, a major tipping point was identified when rates of RSL rise exceeded a threshold (8-9 mm yr^{-1} in (Kirwan et al. 2016b), although these numbers do not necessarily apply directly to coastal Louisiana). Under such conditions, widespread inundation is predicted with a rapid reduction in wetland extent, similar to what has been observed for the early Holocene in the Mississippi Delta (Törnqvist et al. 2020). We note that wetland sites in our study area which would constitute the nucleus for landward retreat (i.e., those farthest landward that abut gently sloping uplands; triangles in Fig. 4A and Extended Data Fig. 5) dominantly (96%) fall in the give-up category. This is consistent with the model results (Kirwan et al. 2016b) predicting that marsh interiors are particularly vulnerable, with higher resilience near the open coast (as seen in Fig. 4A), corresponding to the inundation scenario where drowning commences in the marsh interior until the seaward edge ultimately jumps landward. This results in a fringing marsh with a much reduced footprint (Törnqvist et al. 2021).

Climate change and elevated CO_2 levels may enhance vertical accretion in coastal wetlands by biological feedbacks, another potential mechanism through which wetlands might counterbalance rising sea levels in the future (Morris et al. 2002, Kirwan et al. 2016a, Cahoon, McKee and Morris 2021). To test this, we compared the rates of RWL change and SEC at all monitoring sites (excluding a small number of outliers) in addition to a subset of sites with high organic-matter content, where biological feedback is more likely to dominate vertical accretion. Our data show no correlation for either case. In other words, we see no evidence for the ecogeomorphic feedback proposed by previous studies (Morris et al. 2002, Kirwan et al. 2016a, Cahoon et al. 2021). Despite the extremely high median rate of RWL rise in coastal Louisiana, 13% of our sites are not yet in give-up mode. These “safe” sites experience a median RWL rise of 9.2 mm yr^{-1}, i.e., much lower than the overall median. This subset of resilient wetland sites also features SEC rates that are twice as high as the median for the entire data set (11.2 vs. 5.6 mm yr^{-1}). Given our finding that sites with lower rates of RWL rise tend to see higher SEC rates, we postulate that the rates of RWL rise in our study area are well above those where biological productivity benefits from increased flooding.

The median surface-elevation deficit for all monitoring sites during the study period is 8.0 mm yr^{-1}, suggesting that even with a considerably lower rate than the observed GSL rise, widespread wetland collapse is likely to occur. Subtracting the median surface-elevation deficit from the observed rate of GSL rise yields 2.5 mm yr^{-1}, a condition where about half of the monitoring sites would be able to track GSL rise. This is consistent with an earlier study (Jankowski et al. 2017) that adopted a GSL rise rate of only 2 mm yr^{-1} and found about half of the monitoring sites to be in deficit. We also examine the outcome for the 25^{th} percentile which corresponds to a surface-elevation deficit of 3.5 mm yr^{-1}. A similar subtraction yields a value of 7 mm yr^{-1}, suggesting that under such a rate of GSL rise about 75% of sites would be in deficit.

According to the Sixth Assessment Report of the IPCC (IPCC 2021), with policies currently in place, we are approximately following Shared Socioeconomic Pathway (SSP) 2-4.5. Projections of GSL rise along the Louisiana coast indicate that even under SSP1-2.6 (which would require Paris Agreement objectives to be achieved), the rate of GSL rise is very likely to exceed 2.5 mm yr^{-1}, putting at least half of the sites in danger of drowning. Under SSP2-4.5, GSL rates are projected to surpass 7 mm yr^{-1} by 2070. As a result, it is plausible that ~75% of the wetlands will lack the resilience necessary to withstand rising sea-level by 2070 under the present climate scenario. Under SSP3-7.0, it is more likely than not that the rate of GSL rise observed over the past decade will be reached by the end of this century, with ~90% of wetlands drowning as a result.

Conclusions

In this project, we examined coastal ecosystem change during 12 years of unusually rapid, albeit likely temporary, sea-level rise (>10 mm yr^{-1}) in the Gulf of Mexico. Such rates, which may become a persistent feature in the future due to anthropogenic climate change, drove rising water levels of similar magnitude in coastal Louisiana and thus affected the ~15,000 km^2 of coastal wetlands in this region. Measurements of surface-elevation change at 253 monitoring sites show that 87% of these sites are unable to keep up with rising water levels. We find no evidence for enhanced wetland elevation gain through ecogeomorphic feedbacks, where more frequent inundation would lead to enhanced biomass accumulation that could counterbalance rising water levels. We attribute this to the exceptionally rapid sea-level rise during this time period. Under the current climate trajectory (SSP2-4.5), drowning of ~75% of Louisiana's coastal wetlands is a plausible outcome by 2070.

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Application of research to implementation of Coastal Master Plan: Bulleted list of suggested applications

- We show that the rate of geocentric sea-level rise off the Louisiana coast is closely mirrored by the rate of relative water-level rise in the Louisiana wetlands, particularly at sites in the Mississippi Delta that are not too far inland
- We examine the likelihood of wetland drowning in 2070 under different climate scenarios
- We demonstrate the particular vulnerability of the Chenier Plain, which is likely linked in part to local hydrological conditions
- We show extremely high rates of relative water-level rise in the Birdfoot delta which is likely due to exceptionally high subsidence rates

B. DELIVERABLES

*Note – please submit all PDFs of reports, papers, and presentations with the final report **in the portal (LA-COE Apply)**. Thank you!*

1. **Deliverables on proposed goals and objectives.** If a goal or activity is not completed, please describe in the "comments" why actual output / deliverable deviated from the proposed.

#	Proposed goal / objective / activity	Target output / deliverable	Completed (Y/N)	Comments	Topical area (s) and research need(s) addressed (as described in the proposal)
1	RSET-MH analysis	Wetland surface-elevation changes	Y		RSET-MH analysis
2	GNSS analysis	Deep subsidence rates	N	This will be added during the revision stage of the manuscript that we are currently working on	GNSS analysis
3	Geomechanical modeling	Subsidence rates due to sediment compaction	N	This work continues, in close cooperation with Wageningen University	Geomechanical modeling
4	Geocentric sea-level analysis	Geocentric sea-level rise rates	Y		Geocentric sea-level analysis
5					
6					
7					
8					

2. Peer-reviewed publications. Please provide .pdf copies of all publications.

Authors	List author names of graduate students/postdocs	Title	Journal	DOI (or other identifier)	Published; submitted; in prep; planned?	Date
Mark A. Zumberge, Surui Xie, Frank K. Wyatt, Michael S. Steckler, Guandong Li, William Hatfield, Donald Elliott, Timothy H. Dixon, Jonathan G. Bridgeman, Elizabeth L. Chamberlain, Mead Allison, Torbjörn E. Törnqvist	Guandong Li	Novel Integration of Geodetic and Geologic Methods for High-Resolution Monitoring of Subsidence in the Mississippi Delta	Journal of Geophysical Research: Earth Surface	https://doi.org/10.1029/2022JF006718	Published	08/22/2022
Guandong Li, Torbjörn E. Törnqvist, Sönke Dangendorf	Guandong Li	First real-world time-travel experiment shows ecosystem collapse due to climate change	Nature Communications	https://doi.org/10.21203/rs.3.rs-3353228/v1	Under revision	10/02/2023

3. **Oral presentations and posters.** Please provide .pdf copies.

Presenter	Co-authors	List author names of graduate students/Postdocs	Title	Oral or poster?	Conference or meeting name	Date	Proceedings published? (Y/N)
Guandong Li	Torbjörn Törnqvist, Anjali Fernandes	Guandong Li	Spatial-temporal analysis of shallow subsidence rates in coastal Louisiana based on 300 points observations covering the past 10+ years	Oral	AGU Fall Meeting	12/13/2021-12/17/2021	N
Guandong Li	Torbjörn Törnqvist, Sönke Dangendorf	Guandong Li	Time traveling to 2100: wetland response under accelerated sea-level rise along the US Gulf Coast	Poster	State of the Coast Meeting	05/31/2023-06/02/2023	N
Guandong Li		Guandong Li	Unveiling vertical land motion: Insights from coastal Louisiana to the US Gulf Coast	Oral	Gulf Sea Level Variation and Rise: All-Hand Meeting	08/16/2023	N

4. **List other products or deliverables**. These can include white papers, patent applications, workshops, outreach activities/products. Describe and provide .pdf copies, as applicable.

Interviewed by Washington Post Climate Reporter Chris Mooney regarding the recently submitted manuscript (https://www.washingtonpost.com/climate-environment/interactive/2023/new-orleans-sea-level-hurricane-wetlands/).

5. **Data.** Making data publicly accessible in a timely manner is a key goal of the data management policy of RESTORE Act Center of Excellence. All projects must ensure that data and ISO metadata are collected, archived, digitized, and made available using methods that allow current and future investigators to address new questions as they arise. Per the U.S. Department of the Treasury's Office of Gulf Coast Restoration Data Accessibility and Management Best Practices[1] *"Data are generally expected to be made publicly available at the time of publication of a peer- reviewed article relying on the data or two years after the data are collected."* All information products resulting from funded projects must be associated with detailed, machine-readable metadata (ISO format) and shared in a regional or national digital repository or data center (e.g., National Centers for Environmental Information, Gulf of Mexico Research Initiative Information & Data Cooperative, Inter-university Consortium for Political and Social Research, DataOne Dash) for discovery and long-term preservation. Metadata, a brief description of the data, and location of the data (e.g., repository, DOI) must be provided to the LA-COE to enable tracking of all data and information products.

#	Data Title	Data Description	Repository or Data Center	Date by when it will be publicly available (1 year after final report)	DOI link (if already available)
1	RSET-MH data	Surface-elevation change – marker horizon time series (2009-2021)	Coastwide Reference Monitoring System	Available in real time	https://cims.coastal.la.gov/monitoring-data/
2	Relative water-level data	Water level time series (2009-2021)	Coastwide Reference Monitoring System	Available in real time	https://cims.coastal.la.gov/monitoring-data/
3	GNSS data	Global Positioning System time series (2009-2021)	Nevada Geodetic Laboratory	Available in real time	http://geodesy.unr.edu/
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[1] https://www.fio.usf.edu/documents/flracep/program-documents/Treasury%20RESTORE%20COE%20data%20management%20best%20practices%20Jan%202018.pdf

6. **Mentoring and Training.** Please list post-doctoral and graduate and undergraduate student participants (provide .pdf copies of thesis/dissertation).

First Name	Last Name	BS/MS/PhD/Postdoc	# Years involved	Institution	Thesis/Dissertation Title/Research Topic or Tasks	Did the student graduate? (Y/N)	If they graduated, current position/location?
Guandong	Li	PhD	2	Tulane University	Deciphering the mechanisms of subsidence, relative sea-level change, and their impacts on coastal regions	N	
Kayla	Willis	Undergraduate student	0.5	Tulane University	Tropical cyclones and dynamics of wetland surface elevations	N	

C. CERTIFICATION

Certification: I certify to the best of my knowledge and belief that this report is correct and complete for performance of activities for the purposes set forth in the award documents.

Principal Investigator: Torbjörn Törnqvist

Signature:

Name: Torbjörn Törnqvist

Date Signed: 11/27/2023

Approval: I have evaluated the final report and associated invoice and confirm that the project is finished.

LA-COE Technical Point of Contact:

Signature: Jessica R. Henkel

Name: Jessica Renee Henkel

Date Signed: 12/8/2023

Approval: I have reviewed the final report and approve for payment.

LA-COE Director:

Signature: Jessica R. Henkel

Name: Jessica Renee Henkel

Date Signed: 12/8/2023