PROJECT INFORMATION

Project Director's Name*	Sarah Lester
Organization*	Florida State University
Project Title*	Developing an Integrated Monitoring and Assessment Framework for Evaluating Ecosystem Service Outcomes from Seagrass Restoration in the Gulf of Mexico
Reporting Period*	2/1/18-1/31/22

Note to Grantees: In sections 1 to 5, we ask you to highlight your accomplishments (including outputs and outcomes) through this grant award. These sections of the final grant report will be made available to the public.

1. GOALS AND ACCOMPLISHMENTS

1.1 Please restate the goals and objectives of your project.*

Seagrass restoration is a major priority for the Gulf of Mexico, including the Florida Gulf Coast (FGC), because of long-term degradation of seagrass habitat by human impacts and a growing appreciation for the many benefits that healthy seagrass beds provide to people (i.e., ecosystem services). However, these ecosystem services are rarely quantified and tracked as part of monitoring programs, likely due to limited resources and the lack of consistent approaches for measuring ecosystem service delivery across locations. To address this gap, the proposed work aims to develop a general framework for monitoring and assessing the ecosystem service outcomes of seagrass restoration, focusing on the FCG as an initial case study. The framework will rely on spatial modeling approaches to guide and supplement limited restoration and monitoring resources. The project will focus on the following objectives:

1) Compile spatial data on the distribution of seagrasses and identify areas throughout the FGC that could be suitable for seagrass restoration employing a species distribution modeling approach.
2) Develop spatial models of ecosystem service delivery for three important seagrass services: nursery habitat for fished species, biodiversity augmentation, and blue carbon storage. Models will be applied to existing seagrass beds and used for quantifying the services that would be provided by restoring seagrass at suitable sites.
3) Validate ecosystem service models and ground-truth outputs through targeted field sampling.
4) Identify metrics, either based on direct sampling or modeled indicators, to track ecosystem services provided by seagrasses. A key aspect will be to determine when direct monitoring of services can be replaced by either predictive models or commonly monitored seagrass metrics as proxies, facilitating more cost-effective ecosystem service accounting.
5) Conduct tradeoff analyses examining tradeoffs in achieving different ecosystem service outcomes and from restoring seagrass in different locations. A tradeoff analysis could be applied to pending restoration proposals for the FGC to identify projects that provide the best value per restoration cost.
6) Disseminate project outputs (maps, models and tradeoff analysis results) to relevant practitioners in the region through meetings, conferences, webinars, and an interactive website.

The outputs produced by this project will include maps of seagrass habitat suitability and service delivery, predictive spatial models of seagrass services, and a tradeoff analysis framework to compare the service outcomes and costs of different restoration projects. These outputs will fill key gaps in our scientific knowledge about the functioning of this important but widely threatened nearshore habitat and will reveal potential synergies and tradeoffs in ecosystem service outcomes for seagrass beds. Project outputs will also be immediately applicable to seagrass management, restoration planning, and decision-making about restoration priorities.

Additionally, by identifying which services can and cannot be reliably predicted from existing data, this project will help identify reliable service proxies and direct limited funds towards key gaps in monitoring. Rigorous frameworks for accounting for the ecosystem service benefits of habitat restoration are greatly needed, and will enable better targeting of limited restoration funds and more comprehensive evaluations of restoration projects.

1.2 Describe the accomplishments of your project. You should include both the anticipated accomplishments that you outlined in your project proposal as well as any *unanticipated* accomplishments that have since occurred. Describe any activities you have conducted, programmatic progress made, or project benchmarks and milestones met.*

Over the course of the project, we made the following accomplishments:

Mapping seagrasses using remotely-sensed satellite data:
Current seagrass mapping efforts in the state are based on temporally inconsistent and spatially incomplete data sources, with data limitations arising in large part from the fact that data collection methodologies – aerial surveys and field surveys – are expensive and time-intensive. To attempt to overcome these limitations and to provide a more comprehensive and consistent mapping product for the state, we are attempting to use freely-available, remotely-sensed Landsat satellite imagery to map seagrass beds along portions of the Florida Gulf Coast. Landsat provides both a good historical and temporal resolution (the data span 1984-present with a 16 day revisit time) and moderate spatial resolution (30m pixel). In Year 2, Dr. Lester's student, Tyler Lynn, as part of his MS thesis, developed a random forest supervised classification model for the Big Bend region of the Florida Gulf Coast (Eastpoint to Horseshoe Beach FL) using Landsat 5 imagery for 1996, 2001, 2006, and 2011. This classification model identifies pixels of seagrass within these images with accuracies ranging from 78% to 88% for the seagrass class. Interestingly, and counter to the prevailing narrative of seagrass degradation throughout the Gulf coast, approximately 290 km2 of seagrass were gained from 1996-2011, with only 116 km2 lost in this same time period according to these classifications (Lynn, FSU MS Thesis, 2019). However, we are concerned that model accuracy is not as high as it needs to be to reliably inform decision-support models and tools for seagrass restoration and management, and in particular we are concerned that the model over-predicts seagrass. We are continuing to work on refinements to the model to improve accuracy and to enable the model to use the most current Landsat imagery. Tyler defended his thesis in August 2019 and is working on a PhD at the University of Georgia working on a different topic, so this work is moving forward slowly, with the goal to finish the model and submit a manuscript in Fall 2022. This was not part of our original project goals, and none of our other research goals were dependent on it, but it will represent a useful product supporting the overall goals of the project.

Developing spatial models of potential seagrass cover and species composition along the FGC:
In order to identify areas throughout the Florida Gulf Coast (FGC) that could be suitable for seagrass restoration, and to model spatial patterns of ecosystem service delivery from seagrass given spatially incomplete mapping of current seagrass, we need a spatial model of seagrass distribution for the study region. We have developed spatially continuous model predictions (i.e., mapped predictions) of expected seagrass meadow attributes, including total seagrass cover and the probability of occurrence of the dominant seagrass species (i.e., turtle grass, manatee grass and shoal grass) for the entire FGC including all subtidal areas within the 4m depth contour.

Our models are based on existing seagrass monitoring datasets from the Florida Fish and Wildlife Conservation Commission's Fishery Independent Monitoring (FIM) program. Using generalized additive mixed models (GAMMs), we related each seagrass response variable (i.e., total cover and species occurrences) to potential predictors that are expected to influence seagrasses in Florida and other regions, including environmental and seascape variables (e.g., depth, bottom type, nutrients, light, salinity, ocean temperature, distance to nearest river, etc.). We also accounted for seasonal and inter-annual trends as well as geographic variation or spatial autocorrelation in the model. We identified important predictors of total seagrass cover and the probability of seagrass species by performing model selection using a full subset information theoretic approach. We used Aikaike's Information Criterion (AIC) to identify the best model for each seagrass response. Then the performance of the resulting models was then assessed by comparing goodness of fit metrics (i., AUC & adjusted R Squared values) and conducting various validation procedures.

We generated mapped predictions of total seagrass cover and species composition across the study area using the seagrass models described above and spatial layers of important model predictors. We averaged monthly predicted seagrass values per 93m by 93m pixel across the summer growing season (June – September) and the years 2016-2020 to obtain maps representing the time-averaged predictions of seagrass cover and the probability of occurrence for the three seagrass species given current environmental conditions. We considered the total predicted distribution of seagrass beds to be the spatial extent of all locations with a predicted total seagrass cover of > 5%. Our models suggest that seagrass beds have a predicted distribution of 9,195km2 along the FGC under current environmental conditions. 6540km2 (71%) of that distribution corresponds to confirmed seagrass beds that have been mapped using aerial surveys; the remaining areas are not confirmed to have seagrasses but are predicted to be able to support them, i.e., they are either unconfirmed existing beds or potential restoration areas.

We also developed sea level rise scenarios, based on the IPCC RCP 8.5 scenario that predicts sea level rise of 0.61 to 1.1 m above current sea level by 2100, and examined how our seagrass model predictions would change assuming +0.5m and +1.0m of sea level rise. Specifically, for these two scenarios, we adjusted depths based on SLR, identified a new shoreline based on adjusted depths, and accounted for changes to light availability with changing depth profiles. We then generated mapped predictions of total seagrass cover and species composition under these two sea level rise scenarios. This allows us to examine how management and restoration priorities might change in the future given the impending threat of sea level rise. Our model projections indicate that sea level rise could result in significant losses of current seagrass beds and potential restoration areas, causing contracted distributions and lower seagrass cover.

This work was led by PhD student Jenn McHenry as part of her dissertation, under the mentorship of Drs. Lester and Rassweiler. The seagrass models described here are part of a manuscript published in Diversity and Distributions (McHenry at al. 2021). The paper also includes our biodiversity enhancement model, described below.

These spatial models of seagrass distribution, cover and species composition, under current conditions and future sea level rise, are an important input to all of our ecosystem service models described below, and should generally be a useful resource for managers and restoration practitioners in Florida. Accompanying the paper, we also created a decision support tool in RShiny to disseminate the results of the seagrass models and to allow for consideration of potential changes in the predicted total cover of seagrasses with sea-level rise and successful habitat restoration (http://jennifermchenry.shinyapps.io/seagrass_bev).

Developing spatial models for ecosystem services from seagrass beds along the FGC:
Seagrasses provide a broad array of benefits to people – known as ecosystem services – including carbon storage, nursery habitat for fished species, biodiversity augmentation, improved water clarity, recreational opportunities, erosion control and coastal protection. One of the primary goals of our project is to develop spatial models of ecosystem service delivery from seagrass beds to examine spatial patterns of seagrass services in this region and whether different services are correlated in space. We can also apply these models to various management and restoration scenarios, and use them to explore potential synergies and tradeoffs among services and to identify restoration sites that are most likely to maximize a suite of services. The majority of this work, including all of the spatial models of ecosystem services described below, was led by PhD student Jenn McHenry as part of her dissertation, under the mentorship of Drs. Lester and Rassweiler.

Spatial model of faunal biodiversity enhancement from seagrass:
Seagrasses support a variety of important fish and invertebrate species either seasonally or year-round that depend on healthy seagrasses for shelter, food, foraging, and/or mating habitat. To develop spatial models of the role of seagrass in supporting overall biodiversity, we developed a model of how spatial variation in seagrass cover and community structure influences patterns of coastal marine biodiversity along the FGC using the Florida Fish and Wildlife Conservation Commission Fisheries Independent Monitoring (FIM) dataset. These data quantify monthly abundance and population trends for all life-stages of fished species, including fish and invertebrates, found in major bays and estuaries on the Florida Gulf Coast, while also collecting a range of parameters relevant to quantifying variability in biodiversity augmentation. Following a similar approach to the potential seagrass model described above, we used GAMMs to relate faunal species richness to seagrass variables (i.e., seagrass cover, seagrass species richness, and seagrass species composition). We also controlled for possible covariates of seagrass-associated biodiversity in this region, such as environmental conditions (e.g., depth, temperature, oxygen, and sediment properties), seascape features (e.g., proximity to shore and connectivity with other biogenic habitats), temporal trends (e.g., seasonality and interannual) and geographic factors (e.g., latitude and longitude). We then are able to generate map predictions of faunal biodiversity using the final models and spatial layers for important model predictors, mapping the time-averaged summertime faunal biodiversity.

We then evaluated three scenarios to estimate the biodiversity enhancement value of seagrass beds, i.e., the number of additional species supported by the presence of seagrass per sampling event. For each scenario, we compared model predictions of faunal biodiversity assuming seagrass beds are present at the level predicted by our seagrass models to those representing various counterfactual conditions.

1) A current enhancement value scenario was geographically constrained to the extent of confirmed seagrass beds (i.e., areas that have been previously surveyed and found to have seagrass beds by Florida FWCC aerial surveys between 1985 and 2019; http://geodata.myfwc.com/). We compared current conditions to counterfactual conditions where all existing seagrass beds are lost from the study area. We calculated the current enhancement value as the spatially-explicit difference in predicted faunal biodiversity between the current and counterfactual scenario.

2) A enhancement value with restoration scenario was constrained to areas where seagrass beds are absent from FWCC maps but could potentially survive if restored according to seagrass model predictions (i.e., locations with predicted total seagrass cover > 5% outside of confirmed seagrass beds). The counterfactual conditions presumed that these areas are restored to the level of seagrass cover predicted by our models. We calculated the enhancement value with restoration as the difference in predicted faunal biodiversity between the counterfactual restoration scenario and the continued absence of seagrass beds.

3) A enhancement value with sea level rise scenario was constrained to the total predicted distribution of seagrass beds at the current sea-level, plus those areas that could become suitable for seagrass beds at 2100 according to model projections (i.e., locations with a projected total seagrass cover > 5%) during +0.5m and +1.0m sea level rise. We quantified the biodiversity enhancement value of these future projected seagrass beds by comparing faunal biodiversity predictions assuming biodiversity is present at the levels predicted by our models, to those that presumed seagrasses are totally lost from the study area by 2100. We calculated the future enhancement value as the spatially-explicit difference in faunal biodiversity between the two predictions.

The results of our models suggest that current seagrass beds support 43-64% more species than unvegetated habitats, even when accounting for spatial variability in predicted faunal richness due to environmental, seascape, temporal, and geographic factors. Seagrass restoration in potential habitats would also increase biodiversity in the near-term (i.e., 43-45% above unvegetated levels). However, model projections accounting for sea level rise suggest there could be significant reductions in the enhancement value provided by seagrasses, although there could also be many suitable locations for seagrasses by 2100, with some having either comparable or potentially increased enhancement value.

These results highlight the need to carefully select conservation and restoration areas, in order to minimize potential losses of seagrass and associated species due to sea level rise.

These models are part of a published paper that includes the seagrass distribution models (McHenry et al. 2021). We also include the model results for biodiversity enhancement in the RShiny decision support tool described above, allowing for consideration of potential changes in biodiversity enhancement value over a regional spatial scale and with sea-level rise and successful habitat restoration (http://jennifermchenry.shinyapps.io/seagrass_bev).

Spatial model of nursery habitat for fished species:

Many commercially and recreationally important fish and invertebrate species spend at least part of their early life-cycle within seagrass meadows, supporting commercial and recreational fishing value. However, the value of seagrass meadows as potential nursery habitat could vary substantially across space based on many geographic, ecological, and environmental factors. We are developing spatial models for quantifying and predicting the nursery habitat value of seagrasses along the FGC, operationalized as the probability of encountering juvenile life stages of fished species within seagrass meadows. Since nursery habitat value is likely to be species-specific, we are focusing on a few representative fished species, including snappers (i.e., gray and lane), sheepshead, spotted seatrout, white grunt, and pink shrimp.

The models relate observed species occurrences for juvenile life stages (from the FIM data mentioned above) to variables representing local conditions that could influence rates of settlement, recruitment and survival for juveniles in different locations. Potential covariates for each species model include seagrass community attributes, proximity to other potential nursery and adult habitats (e.g., coral reefs and mangroves) and environmental variables such as ocean temperatures, salinity, and primary productivity regimes. We also control for monthly, inter-annual, and geographic variation. We are using generalized additive models (GAMs), and are scaling up model predictions for each nursery species by combining model outputs with spatial layers for significant model predictors, allowing for mapped predictions for the expected probability of juvenile occurrence for each species at unsampled locations across the study area. We evaluate the model performance and predictive skill of each nursery model, using similar approaches used for the seagrass and faunal biodiversity models described above.

We evaluate the nursery enhancement value of seagrass beds, i.e., the additional probability of encountering nursery species resulting from the presence of seagrass, following a similar approach described above. For each species, we estimate the current nursery enhancement value as well as the nursery enhancement value of restoration. Then we create a composite map depicting spatial variation in the total nursery value (i.e., recreational + commercial value) of seagrass meadows. To capture the influence of seagrass on recreational and commercial fisheries separately, we also create composite maps with different weighting schemes based on the annual commercial fishery revenue and recreational catch for each species from FWCC's commercial fishery landings database (https://myfwc.com/research/saltwater/fishstats/commercial-fisheries/landings-in-florida/NOAA) and the NOAA Marine Recreational Information Program (https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries).

The final nursery models for six recreationally and commercially fished species (i.e., sheepshead, spotted seatrout, gray and lane snapper, pink shrimp, and white grunt) perform well at describing spatial variation in historic observations of juvenile life stages (AUCs=0.89 - 0.95) and maintain their high predictive skill during model validation steps (AUCs=0.86 - 0.95). This indicates these models are useful for inferring spatial variation in the nursery habitat value of seagrass meadows across unsampled locations and for anticipating the recovery of nursery services from seagrass restoration areas. Model results indicate that the probability of encountering nursery species is linked to a variety of seagrass, environmental, and seascapes factors and that the importance of model predictors is highly species specific. For example, the probability of encountering juvenile pink shrimp increases with the presence of shoal grass presence, at lower dissolved oxygen oxygen levels, at moderate minimum annual temperatures, and closer to shore. Meanwhile, the juvenile gray snapper increases with the total cover of seagrasses, with distance away from river outlets, and where there are higher minimum annual ocean temperatures. Our results indicate that the total nursery enhancement value of seagrasses is likely to be context dependent.

Spatial model of blue carbon:

By removing carbon dioxide from the water column and converting it to extensive leafy meadows, root systems, and detrital pools, seagrasses perform an important carbon storage function, often referred to as ‘blue carbon’. Carbon storage is likely to vary spatially based on seagrass species composition, nearshore hydrodynamics, physical disturbance, water quality, sedimentation, and the proximity of potential carbon sources. However, there is a paucity of data on blue carbon stocks associated with seagrasses in this region and the relative influences of these factors remains unclear. Therefore, we have needed to collect and analyze our own field and laboratory data in order to develop a spatial model for blue carbon stocks in Florida seagrasses. To identify suitable indicators for carbon stocks in seagrass meadows along the FGC, we collected seagrass community survey data, sediment cores, and seagrass clippings in triplicate from 46 different sampling locations across the Florida Gulf Coast focused within St. Joseph Bay, Apalachee Bay, Deadman's Bay, and Crystal Bay.

Laboratory analysis of the biomass and sediment core samples have provided us with estimates of carbon stocks contained within the above-ground biomass, below-ground biomass, and sediments of different seagrass meadows. To estimate carbon stocks in above-ground biomass, seagrass clippings have been sorted by species and analyzed in the lab for dry weight. To obtain estimates of sedimentary carbon stocks, each sediment core has been subsetted into 2cm slices, dried, and combusted at two different temperatures (i.e., 450 deg C and 950 deg C) to obtain measurements of the fraction of organic and inorganic material. For a third of the cores, a subsample is also being sent off for further analysis at the Duke Devil Lab and the Florida International University Blue Carbon Analysis Laboratory to obtain measurements of the fraction of organic and inorganic carbon, which we use to convert all measurements of organic and inorganic matter to carbon stocks. Some slices from each core have also been analyzed for grain size, which provides an additional indicator of the blue carbon stocks. All lab analyses of cores collected have been completed as of January 2022.

The resulting blue carbon model captures how blue carbon stocks contained in the surficial sediments of seagrass beds (i.e., the top 20cm) vary across sampling locations and relate to important indicator variables. During model development, we considered how sedimentary organic carbon stocks relate to the total percent cover, meadow height, and the probability of occurrence and relative cover for dominant seagrass species. We also accounted for possible environmental, seascape, and geographic covariates of carbon storage, such as sediment grain size, water depth, annual nitrates in the water-column, proximity to river inputs and other foundation species , and geographic location. Combining spatial layers for significant model predictors with model outputs (including the seagrass cover maps described above), we have generated mapped predictions for how blue carbon stocks vary across the study area. Following a similar approach described above, we have also evaluated the blue carbon stock enhancement value of seagrass beds and enhancement value with restoration in terms of the additional blue carbon storage resulting from the presence of seagrass.

The final model performs well (Adj-R^2=0.43) and maintains its high predictive skill during cross-validation (Adj-R^2=0.41). Model results indicate seagrasses significantly enhance blue carbon stocks throughout this region. However, we found that variability of sedimentary organic carbon may be more related to the influence of nearby oyster reefs and estuarine gradients in controlling nutrient levels and sediment deposition/resuspension rates than to seagrass community structure. Still, the significant effect of total seagrass cover on sedimentary blue carbon stocks indicates that immense stock enhancement benefits can be gained through the protection and recovery of high cover seagrass beds. This model will support an additional publication, to be submitted in the next few months, focusing on describing the geographic distribution and variability of blue carbon stocks associated with seagrass beds in the Florida Gulf region.

Spatial model of coastal protection:

Seagrasses can also protect shorelines from erosion and storm damage through the dampening of current dynamics and the stabilization of sediments. However, coastal protection services from seagrasses could vary across space depending on the geographic and environmental context. To quantify spatial variability in the coastal protection services from seagrasses along the FGC, we are using an existing model from the Natural Capital Project called the InVEST Coastal Vulnerability model. This model is an open-source platform that produces a mapped qualitative index of coastal exposure to erosion and inundation from storms. As inputs, the coastal protection model uses mapped proxies of various shoreline processes that can influence exposures to erosion and inundation, such coastal geomorphology, the location of natural habitats (e.g., mangroves), coastal topography and bathymetry, as well as estimates of the prevailing storm wind speeds and wave power compiled by WaveWatch. The model also uses spatial data on human population density, acquired through the InVEST API, to produce mapped estimates of where humans are most vulnerable to storms, waves and surge. Although the model does not value coastal protection services directly, it does provide a spatially explicit ranking of coastal exposure and vulnerability to erosion and storms. By comparing how the spatial extent and magnitude of these mapped rankings overlap with the predicted distribution of seagrass meadows, we are able to assess spatial patterns in the supply of coastal protection services from seagrass meadows. Our final model for the Florida Gulf Coast modifies outputs from the Natural Capital Project to indicate the coastal exposure of the nearest shoreline pixel to a given seagrass bed. Our results indicate that seagrass beds generally coincide with shorelines with moderate to high coastal exposure.

Spatial model of recreation value:

Seagrasses can also benefit society by creating opportunities for recreation and tourism. But the value of seagrass meadows to potential recreational users and tourists could vary across space, depending on a range of factors like the attributes of seagrasses, user access, and proximity to other attractions. To quantify spatial variability in the potential recreation value of seagrasses along the FGC, we are using spatial datasets on coastal visitation rates, assembled through the Natural Capital Project's InVEST Recreation Model. This open source modeling platform uses the locations of photographs uploaded to the online social media website, Flickr, as a proxy for coastal visitation rates. Relying on InVest's global Flickr API , we have developed a modified recreation model that relates approximated rates of coastal visitation to variables that may factor into people's decisions about where to recreate, such as ocean temperatures, points of accessibility, and the attributes of and proximity to seagrass meadows. To allow for potential interactions and nonlinear relationships between potential predictors, we developed the recreation model using a generalized additive modeling framework. Combining model outputs with spatial layers for model predictors, we evaluate the correlation between seagrass attributes and recreational activity, controlling for other relevant factors. The resulting model allows for mapped predictions for coastal visitation rates associated with seagrasses, operationalized as the average log transformed photo-user day per pixel across the study area. Following a similar approach to the other ecosystem service models, we are then able to assess the recreation enhancement value of seagrass beds and the recreation enhancement value with restoration in terms of the additional visitation resulting from the presence of seagrass.

The final model performs well (adj-R^2=0.61), accounting for spatial variation in recreational use rates related to the total cover of seagrasses, the presence of other charismatic habitats (e.g., coral reefs, mangroves, and salt marshes), factors affecting coastal travel (e.g., roadways,) and access (e.g., boat-ramps, marinas, and beaches), and population density. An interesting non-linear interaction between seagrass cover and the distance away from beaches suggests that no to low cover of seagrass is preferred for beach-based recreation (e.g., swimming) and that moderate to higher cover of seagrass is preferred for water-based recreation (e.g., boating).

Spatial dimensions of multiple ecosystems services from seagrass beds:

Combining the different ecosystem service models described previously in this section, we are examining the spatial patterns and associations among these different services (biodiversity enhancement, nursery habitat, carbon storage, coastal protection, and recreation and tourism services). This will allow us to quantify areas of high and low supply for individual ecosystem services and explore associations across multiple ecosystem services to understand the potential synergies and tradeoffs of seagrass restoration and management. We are planning three main outputs from this work: 1) a paper focused on describing multi-service spatial patterns of ecosystem service delivery from seagrass beds along the Florida Gulf Coast, 2) a paper examining tradeoffs in achieving different ecosystem service outcomes based on different conservation and restoration scenarios, and 3) fact sheets for managers and restoration practitioners summarizing the key metrics that can be used to monitor ecosystem service outcomes from seagrass beds.

For the multi-service paper (outcome #1), we have used the models described in this section to map the spatial distribution of service delivery along the Florida Gulf Coast, in each case assessed as the enhancement value of seagrass (i.e., how much additional service is provided by the presence of seagrass compared to if seagrass were absent in that location). We are standardizing the ecosystem service enhancement value predictions to allow for easier comparison and identification of locations contributing to the supply of ecosystem services. We are exploring potential associations between ecosystem services by calculating spatial correlations coefficients among the standardized ecosystem service enhancement values, and are visualizing spatial relationships among the service values using heatmaps. Lastly, we are comparing the main drivers of spatial variability in service value to better understand the underlying factors influencing potential tradeoffs and synergies among services. This paper is being led by Jenn McHenry as part of her dissertation; she is currently finalizing results and drafting this paper and we expect to submit the paper by early summer when Jenn is scheduled to defend her dissertation. For the management scenario tradeoff paper (#2), we plan to commence this paper once we have finalized the results for the multi-service paper since it will use those enhancement value maps as an input to the tradeoff analysis. For this paper, to be led by PI Lester, we will specifically examine tradeoffs in achieving different ecosystem service outcomes from conserving and/or restoring seagrass in different locations, examining different relative preferences for the different services and possibly accounting for different sea level rise scenarios. For the monitoring metrics fact sheets (#3), we have developed templates for the sheets and are working to finalize the content before printing and distributing to different practitioner audiences. These fact sheets highlight, for each of the seagrass services we have modeled, how direct monitoring of services can be replaced by either predictive models or commonly monitored seagrass metrics as proxies in order to facilitate more cost-effective ecosystem service accounting.

Evaluating spatial planning approaches to marine ecosystem restoration:

We published a paper in a special feature on marine ecosystem restoration in Frontiers in Marine Science that provides a literature review and conceptual approach for how to apply spatial planning principles to marine ecosystem restoration (Lester et al. 2020). The paper focuses on the need, in marine ecosystem restoration projects, to carefully select locations that will provide the largest return on investment, not just in terms of restoration success but also in terms of ecosystem service outcomes. While restoration site selection at the local scale has received considerable attention in the literature and in practice, site selection at larger spatial scales is often not considered or quantitatively evaluated. Furthermore, site selection tends to focus more on environmental conditions beneficial for the restored habitat, and not on ecosystem service outcomes once the habitat is restored, which may vary considerably from site to site, or on more complex landscape dynamics and spatial patterns of connectivity. In this paper we (1) review recent (2015–2019) scientific peer-reviewed literature for several marine ecosystems (seagrass beds, salt marshes, and mangrove forests) to investigate how commonly site selection or spatial planning principles are applied or investigated in scholarly research about marine ecosystem restoration at different spatial scales, (2) provide a conceptual overview of the rationale for applying spatial planning principles to marine ecosystem restoration, and (3) highlight promising analytical approaches from the marine spatial planning and conservation planning literatures that could help improve restoration outcomes. We argue that strategic site selection and spatial planning for marine ecosystem restoration, particularly applied at larger spatial scales and accounting for ecosystem service outcomes, can help support more effective restoration. This paper provides explicit guidance to managers and restoration practitioners on how to incorporate the ecosystem service models we are developing for seagrass in this project to restoration planning decisions.

2. Outputs

Before the form is completed, you may click "Save & Continue Editing" at the bottom of the page at any time to save your work or "Next" to move onto the next page of this form.

When the form is completed, you may click "Mark as Complete" at the bottom of the page to save your work and return to the dashboard.

** denotes required fields*

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2. OUTPUTS

Outputs are tangible or measurable deliverables, products, data, or publications produced during the project period.

2.1. Please indicate the number of students (K-12, undergraduate, or graduate), postdoctoral scholars, citizen scientists, or other trainees involved in the project. *

Please enter 0 if none were involved.

K-12 students	0
Undergraduate students	6
Graduate students	5
Postdoctoral scholars	2
Citizen Scientists	0
Other Trainees	1

2.1a. Other Trainees *

Please describe who are the "other trainees" involved in your project.

Research technician.

2.2. Has your project generated any data and/or information products? *

Generation of data includes transformations of existing data sets and generation of data from existing resources (e.g., maps and images). Information products include publications, models, software, code, curricula, and digital resources.

(Check all that apply.)

Responses Selected:

Data
Information Products

2.3. Briefly describe how you fulfilled the approved Data Management Plan and, if applicable, any changes from the approved plan. *

This project has involved both the generation of synthetic data products and the collection of new data. Data and information management for this project has primarily taken place at Florida State University, led by PhD student Jenn McHenry in consultation with PIs Lester and Rassweiler. All data products produced have been stored in machine readable open standard formats—either a tabular data format or a GIS layer format (i.e., .shp and .tif files). Data assimilation and analysis has been conducted primarily in RStudio, with all metadata and scripts being saved as open-source formats (i.e.txt and .Rmd files). All assimilated project datasets and scripts have been saved throughout the project on local hard drives, but periodically backed up to an external hard drive and to a DropBox account that is linked to multiple computers.

All field datasets and modeled outputs (including the metadata and documentation for all model structure, model fitting parameters, validation surveys, datasets, and output maps) are being made freely available (pending publication) through the Knowledge Network for Biocomplexity (https://knb.ecoinformatics.org/) as well as Florida State University's DigiNole repository for broad discovery and long-term preservation. Accompanying R scripts are also being made available via GitHub (pending publications) to promote the reproducibility and a broader applicability of our study to other regions with seagrass habitats and other marine foundation species, such as oyster reefs. For the purpose of long-term storage, we are also making arrangements to archive all project outputs (e.g., raw datasets, assimilated datasets, scripts, models objects, modeled outputs, metadata, and scripts) locally using multiple forms of backup. One copy will be kept on a rugged LaCie External Hard Drive and another copy will be kept on a multiple disk storage system with full redundancy (raid-z2) to ensure data will not be lost in the event of drive failure. This multi-disk system is housed in the server room of the King Building at Florida State University.

If your project has generated data, please download the Excel worksheet entitled GRP Data Management Reporting. Use the "Data Report" tab in the worksheet to create an inventory of data sets that you produced and to verify deposit in a curation facility. Upon completion, please upload the worksheet to your task list. If you need guidance on how to complete the Data Report, please e-mail gulfgrants@nas.edu. A member of GRP's data management staff will reach out to you.

If your project has produced publications, websites or data portals, GIS applications, models or simulations, software packages or digital tools, code, curricula, or other interactive media, please download the Excel worksheet entitled [GRP Information Management Reporting]. Use the "Information Products Report" tab in the worksheet to create an inventory of these products and to verify deposit in a curation facility. Upon completion, please upload the worksheet to your task list. If you need guidance on how to complete the Information Products Report, please e-mail gulfgrants@nas.edu. A member of GRP's data management staff will reach out to you.

2.4. Aside from data and information products, what other tangible or measurable deliverables or products (e.g., workshops, trainings, and outreach events) were produced during the project period? *

Upon completion of this form, you may upload supplemental material that represent the tangible or measurable deliverables or products to complement this narrative report.

None.

3. Data Management

Before the form is completed, you may click "Save & Continue Editing" at the bottom of the page at any time to save your work or "Next" to move onto the next page of this form.

When the form is completed, you may click "Mark as Complete" at the bottom of the page to save your work and return to the dashboard.

** denotes required fields*

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3. DATA MANAGEMENT

In this section, please provide a response to each question to complement the **Data Report** in the GRP Data Reporting Excel worksheet.

3.1 If you listed multiple data sets in the data reporting table, please briefly describe how these data sets relate to one another. *

The data management reporting form lists all modeled outputs, in raster format, created from this project. Six raster data layers show the predicted total cover of seagrasses in the Florida Gulf Coast under three sea-level scenarios (current sea level, +50cm above current, +100cm above current) and within different potential management areas (i.e., confirmed seagrass beds and potential recovery areas). Three raster data layers show the predicted probability of encountering three seagrass species (i.e., turtle grass, manatee grass, and shoal grass) at the current sea level within confirmed seagrass beds and with successful restoration of seagrasses within potential recovery areas. Six raster data layers show the predicted biodiversity enhancement value of seagrasses under three sea-level scenarios (current sea level, +50cm above current, +100cm above current) and within potential management areas (i.e., confirmed seagrass beds and potential recovery areas). The final eight raster data layers show the ecosystem service enhancement value of seagrasses expected within confirmed seagrass beds and with successful restoration. These layers are in the process of being made publicly available via the Knowledge Network for Biocomplexity (https://knb.ecoinformatics.org/) and DigiNole (https://diginole.lib.fsu.edu/). The Knowledge Network for Biocomplexity (KNB) is an international repository intended to facilitate ecological and environmental research. FSU's DigiNole is an open-source and public/open access compliant digital platform for disseminating and archiving for all forms of scholarly research outputs, including publications and data. The seagrass and biodiversity enhancement value layers are also already publicly viewable via our Seagrass Biodiversity Enhancement Explorer deployed via RShiny (http://jennifermchenry.shinyapps.io/seagrass_bev).

3.2. Please provide a list of additional documentation to describe the data listed in the reporting table (e.g., code books, lab manuals, workflow procedures). Enter none if you did not produce any additional documentation to describe the data. *

None.

3.3. Beyond depositing data and metadata in a repository, what other activities have you undertaken or will undertake to ensure that others (e.g., researchers, decision makers, and the public) can easily discover project data? What other activities have you undertaken to ensure that others can access and re-use these data in the future? *

We are making all model outputs and field datasets supporting publications publicly available via Florida State University's DigiNole repository (https://diginole.lib.fsu.edu/). DigiNole is an open-source and public/open access compliant digital platform for disseminating and archiving for all forms of scholarly research outputs, including publications and data. We are coordinating with the Public Access Team and Research Repository Specialist at Florida State University Libraries to link all research output submissions to this specific grant project, making all publication and data produced from this grant easily discoverable and accessible. Once all model outputs and field datasets have been uploaded to DigiNole, we plan to add a new data hub section to our project website where potential end users can navigate to and download our datasets (https://www.lester-lab.com/seagrass).

3.4. Are any data products you produced sensitive, confidential, and/or proprietary? *

No

4. Information Products

Before the form is completed, you may click "Save & Continue Editing" at the bottom of the page at any time to save your work or "Next" to move onto the next page of this form.

When the form is completed, you may click "Mark as Complete" at the bottom of the page to save your work and return to the dashboard.

** denotes required fields*

4. INFORMATION PRODUCTS

In this section, please provide a response to each question to complement the **Information Products Report** in the **GRP Information Products Management** Excel worksheet.

4.1. Please select the type(s) of information products that your project produced. *

Responses Selected:

1. Scholarly publications, reports or monographs, workshop summaries, or conference proceedings
2. Websites or data portals
5. Models or simulations
6. Software packages or digital tools, or other interactive media

Scholarly publications, reports or monographs, workshop summaries, or conference proceedings *

Please provide a list of citations for project publication, reports and monographs, workshop summaries, and conference proceedings.

1) Lester, S. E., Dubel, A. K., Hernán, G., McHenry, J., & Rassweiler, A. (2020). Spatial planning Principles for marine ecosystem restoration. Frontiers in marine science, 7, 328.

2) McHenry, J., Rassweiler, A., Hernan, G., Uejio, C. K., Pau, S., Dubel, A. K., & Lester, S. E. (2021). Modelling the biodiversity enhancement value of seagrass beds. Diversity and Distributions, 27(11), 2036-2049.

3) Grunder, Elizabeth (2019). Analysis of proposed seagrass restoration projects along Florida's Gulf Coast. Florida State University, Undergraduate Honors Thesis. https://purl.lib.fsu.edu/diginole/FSU_libsubv1_scholarship_submission_1638310916_e15d4667

4) Lynn, Tyler (2019). Informing seagrass management and restoration along the Florida Gulf Coast through remote sensing and spatiotemporal analyses of seagrass distribution. Florida State University, Department of Geography, Masters Thesis. http://purl.flvc.org/fsu/fd/2019_Summer_Lynn_fsu_0071N_15444

Websites or data portals *

Please provide a list of project websites and data portals (including the website URL).

1) https://www.lester-lab.com/seagrass

2) https://github.com/jennmchenry1/Modeling-the-Biodiversity-Enhancement-Value-of-Seagrass-Beds

3) http://jennifermchenry.shinyapps.io/seagrass_bev

4) https://knb.ecoinformatics.org/view/doi%3A10.5063%2FF1RV0M44

5) https://knb.ecoinformatics.org/view/doi%3A10.5063%2FF1WM1BT0

How long beyond the grant period will you maintain the project website/data portal and its contents? Please describe plans to archive the website/data portal and its contents after regular maintenance concludes.*

The website will be maintained indefinitely, as it is part of the PI's faculty webpage.

The github repository will also be maintained indefinitely, as part of PhD Candidate Jenn McHenry's professional Github account.

The Shinyapp website will continue to be supported on a basic shinyapp.io account for one year and will then be transitioned and maintained indefinitely on the free version of the shinyapp.io as part of PhD Candidate McHenry's professional account.

Data shared through the Knowledge Network for Biocomplexity currently falls within their free tier for storage, so should be available there as long as the organization keeps hosting free data. KNB is supported by NSF and NCEAS and says their goal is "long-term preservation of the data entrusted to the repository" so it is likely this data will be available for the foreseeable future. Even so, we have arranged for all data, data products, and other project materials to be stored on a multi-disk storage system housed in FSU's King Building server room. This system is run on Raid Z2 and therefore will not lose data even in the case of multiple hard drive failures. If data becomes unavailable via the KNB or DigiNole system due to technical failure or policy changes by those repositories, we will repost data at other repositories, using the FSU based multi-disk system as our ultimate backup.

Curricula for education and training, GIS applications, Models or simulations, Software packages or digital tools, or other interactive media, and Other *

If you produced any additional documentation to describe information products, please provide a list of this documentation (e.g., model or simulation documentation, software manuals, source code annotation).

Not applicable.

4.2. Beyond depositing information products in a repository, what other activities have you undertaken or will undertake to ensure that others (e.g., researchers, decision makers, and the public) can easily discover and access the listed information products? *

We have dedicated sections of our project website to the dissemination of information products, such as publications, reports, and decision support tools, associated with this research. (https://www.lester-lab.com/seagrass).

Project PIs Drs. Sarah Lester and Andrew Rassweiler have a joint lab twitter account (@RassterLab) and Instagram account (@rassterlab) and both have been used to communicate project activities and outputs.

We have also presented our research at conferences, including the following presentations:
1) “Modeling the biodiversity enhancement value of seagrass beds,” The International Biogeography Society, Annual Meeting, In-person presentation.

2) “Modeling the biodiversity enhancement value of seagrass beds”, Geo Hab: Marine Geological and Biological Habitat Mapping Conference, Virtual Talk, 2021

3) “Geographic variation in carbon storage by Florida seagrass beds,” American Association of Geographers Annual Meeting, Virtual Poster, 2021

4.3. Are any of the information products you produced confidential, proprietary, or subject to special license agreements? *

No

5. Project Outcomes

Before the form is completed, you may click "Save & Continue Editing" at the bottom of the page at any time to save your work or "Next" to move onto the next page of this form.

When the form is completed, you may click "Mark as Complete" at the bottom of the page to save your work and return to the dashboard.

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5. PROJECT OUTCOMES

Outcomes refer to the **impact(s), consequence(s), result(s), or effect(s)** that occur from carrying out the activities or outputs of the project. Outcomes may be environmental, behavioral, health-related, or programmatic. Example outcomes include, but are not limited to: increased learning, knowledge, skills, and motivation; policy changes; actions taken by a group as a result of information generated by your project.

5.1. Please describe the outcomes achieved during your project and how they were assessed. For this question, we are interested in learning about the immediate short-term outcomes that have already occurred during or as a result of your project. Do not include long-term outcomes you foresee your work contributing to beyond the end of the project. *

One of the main outcomes we have seen from our project is the influence that it is starting to have on the field of marine ecosystem restoration. Our project focuses on spatial assessment and modeling of ecosystem services from seagrass beds and on using information about the spatial variability of ecosystem services to inform restoration site selection and monitoring metrics. We wrote an important concept paper about these ideas (for any type of marine ecosystem) as part of this project, published in the journal Frontiers of Marine Science (Lester et al. 2020) entitled "Spatial planning principles for marine ecosystem restoration" (https://www.frontiersin.org/articles/10.3389/fmars.2020.00328/full). These ideas seem to be shaping other scholars' research directions and also informing the design of marine ecosystem restoration projects, as demonstrated by the degree to which the paper has already been accessed and cited. Specifically, according to the Frontiers in Marine Science website, Lester et al. (2020) has had 7,085 total views (as of 3/31/22), placing it in the 78th percent of articles published in the same journal for view numbers. It also has 1,741 downloads, placing it in the 87th percent for number of downloads relative to other articles in the journal. According to Google Scholar, the paper has 12 citations, demonstrating its influence encouraging researchers to adopt more deliberate spatial planning approaches for conservation and ecosystem restoration. For example it is cited in a paper titled "Where is more important than how in coastal and marine ecosystems restoration". The paper was also mentioned on Twitter by 31 different users located in 9 different countries.

The project has also resulted in learning and training outcomes, with students being trained in scholarship at the research-practice nexus and developing skills in ecosystem service accounting and modeling and restoration ecology. PhD candidate Jenn McHenry, who has centered her dissertation around this project, is scheduled to defend her dissertation in May 2022 and has already received multiple offers for postdoctoral scholar positions that would apply the skills she developed in this project to new systems and regions. In addition to Jenn, this project has also trained 4 additional graduate students, 6 undergraduate students, and 2 postdoctoral scholars. One undergraduate is now pursuing a career related to marine conservation and restoration as a result of this project, including applying to the prestigious NOAA InFISH internship program. Of the graduate students, two have successfully graduated with Masters degrees. One of the postdoctoral scholars recently accepted a job with the Nature Conservancy. Through the training provided by this project, we have established a pipeline of researchers well equipped to conduct interdisciplinary research and practice related to marine ecosystem restoration, management and conservation.

5.2. We're interested in hearing not just the results of your project but what are their implications for or contributions to:

- **offshore energy system safety,**
- **environmental protection and stewardship, and/or**
- **health and community resilience**

Please describe what you consider to be the most remarkable accomplishment or finding of your project. What can others learn from your accomplishment and finding? How do you see it fitting in with your greater field of study or community of practice? *

Our work, quantifying the benefits provided by healthy seagrass ecosystems along the Florida Gulf Coast and developing spatial models to map variation in ecosystem service enhancement value throughout our study region, is important for highlighting the many benefits provided by this vulnerable and often heavily impacted nearshore ecosystem. Our models quantify the enhancement value of seagrasses for supporting biodiversity, providing nursery habitat for fished species, supporting recreation and tourism, storing carbon to mitigate climate change, and protecting coastal communities from storm surge and erosion. For example, current seagrass beds support 43-64% more species than unvegetated habitats, even when accounting for spatial variability in predicted faunal richness due to environmental, seascape, temporal, and geographic factors. For all of these benefits to coastal communities, or ecosystem services, the existence of seagrass increased the service relative to if seagrass were lost. Furthermore, our models show how the magnitude of the enhancement value for each service varies across the Florida Gulf Coast region, with distinct spatial patterns for each ecosystem service. As a result, important areas for seagrass conservation and restoration vary depending on which services are the top priorities, and our models can feed directly into decision making and environmental protection and stewardship efforts once these priorities are identified. Finally, we have conducted analyses to reveal the vulnerability of seagrass ecosystem services to climate change - sea level rise could result in significant losses of current seagrass beds and potential restoration areas, causing contracted distributions and lower seagrass cover. Reduced seagrass distribution and cover could compromise the population health of associated fauna, the storage of blue carbon, coastal protection, and Florida's vibrant recreation and tourism industry.

6. Communication

Before the form is completed, you may click "Save & Continue Editing" at the bottom of the page at any time to save your work or "Next" to move onto the next page of this form.

When the form is completed, you may click "Mark as Complete" at the bottom of the page to save your work and return to the dashboard.

** denotes required fields*

Note to Grantees: In Section 6, we seek input from you to help us evaluate the Gulf Research Program's funding strategy. <u>This section will not be made available to the public.</u>

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6. Information to Inform GRP Evaluations

6.1. Sharing the difficulties you encountered helps us learn from your experience. Describe any challenges you encountered in your project and how you addressed or overcame them. Challenges are inherent to conducting any complex project. These may include (but are not limited to): unexpected staffing changes, changes in the community you are working in, appearance of a new technology or dataset in the field you are working in, challenges accessing a field site, policy or regulatory changes that affect the issue you are addressing, low recruitment rates, delays in setting up services, or other problems in implementing and conducting your project. *

We had intended to use the Seagrass Recovery Model developed by named project collaborator Paul Carlson (Florida Fish and Wildlife Research Institute) as an input for identifying areas that could be suitable for seagrass restoration. However, we were unsuccessful in getting access to Carlson’s model or engaging him on the project despite his encouragement of our proposal, which included him providing a letter of support as a project collaborator. We understand he has many demands on his time as an agency scientist, and we adapted our project accordingly.

We adjusted our plans and developed a seagrass distribution model that allows us to construct a spatially-explicit map of where seagrass could occur and identify areas currently lacking seagrass that could be favorable candidates for restoration, including under different sea level rise scenarios. By developing a seagrass distribution model, we have constructed a spatially-explicit map of where seagrass could occur and identifying areas currently lacking seagrass that could be favorable candidates for restoration. We also experienced long waits with getting permits to collect sediment cores for our carbon storage work. Additionally, we faced challenges from COVID related research disruptions, and we detailed those in a no-cost extension request which was approved, which we greatly appreciate. However, we found that COVID-19 impacted not only our research plans, but our ability to conduct in person outreach during the grant period (such as our planned in person workshop). As a result, while we have been able to achieve our desired outputs, many of our intended outcomes focusing on influencing practitioners will not be realized until after the end of the grant, as we will have more opportunities to reach end users and share our project results.

6.2. We like to hear about what you learned from your work and how you feel it affects future work or the work of others. Think back on your project strategies, methods, and activities, what worked and what did not? Is there anything you would do differently in the future? If so, tell us what and why. *

Lessons learned from this work include:

1) Permitting for research activities, particularly when multiple state or federal agencies are involved, can be incredibly slow and requires many months of advanced preparations.

2) Florida Fisheries Independent Monitoring (FIM) dataset offers remarkable power for describing Florida’s nearshore ecosystems but required considerable up front investment to use given its size and complexity, particularly the range of overlapping methods used to sample the ecological community.

3) The scale of model predictions is currently limited by the spatial resolution and time scale of remotely sensed and modeled data products. We are able to produce model predictions of seagrass distribution and ecosystem service enhancement at the 1-hectare resolution. Uncertainty estimates surrounding our predictions are reasonable considering the complexity of marine ecosystem processes. However, we expect these uncertainty estimates could be substantially reduced as higher resolution environmental and oceanographic datasets become available.

4) When developing models of ecosystem services resulting from a particular ecosystem type or foundation species (e.g., seagrass beds), it is important to model a counterfactual of the level of service that would be expected in each location in the absence of the ecosystem or foundation species. In order to be able to accurately inform management and restoration decisions, it is critical that we assess the enhancement value, not just the absolute delivery of the service, particularly when making such assessments in a spatial context over larger geographic scales.

5) In some cases, once accounting for expected climate change impacts like sea level rise, ecosystem conservation might be more useful than restoration. It is important to assess the ecosystem service benefits of conserving existing seagrass beds versus restoring potential seagrass beds, both under current and expected future conditions, in order to more strategically allocate limited resources for seagrass management.

6.3. What are the next steps for this work, either for you and your project team or other researchers? Has this project led to other opportunities to work in this area? *

Over the next 6 months, we will be working on several direct extensions of the work we have completed thus far. As mentioned earlier in the report, we are finishing work on a multi-service paper. This paper uses the individual ecosystem service models we have developed to map the spatial distribution of service delivery along the Florida Gulf Coast, in each case assessed as the enhancement value of seagrass (i.e., how much additional service is provided by the presence of seagrass compared to if seagrass were absent in that location). We are standardizing the ecosystem service enhancement value predictions to allow for easier comparison and identification of locations contributing to the supply of ecosystem services. We will explore potential associations between ecosystem services by calculating spatial correlations coefficients among the standardized ecosystem service enhancement values, and will visualize spatial relationships among the service values using heatmaps. Lastly, we will compare the main drivers of spatial variability in service value to better understand the underlying factors influencing potential tradeoffs and synergies among services. We are also planning to write a paper that examines management scenarios, specifically examining tradeoffs in achieving different ecosystem service outcomes from conserving and/or restoring seagrass in different locations. This could include examining different relative preferences for the different services and accounting for different sea level rise scenarios.

Going forward, we also plan to conduct in person outreach to disseminate the results of our project (both key messages and data products we have produced). We are finalizing fact sheets that summarize the key take-aways from our work for practitioner audiences and the general public. These fact sheets highlight, for each of the seagrass services we have modeled, how direct monitoring of services can be replaced by either predictive models or commonly monitored seagrass metrics as proxies in order to facilitate more cost-effective ecosystem service accounting. We have supplies to print these fact sheets, and plan to disseminate them at in-person events in the Big Bend region of Florida in 2022, post them on the internet (https://www.lester-lab.com/seagrass), and send samples to organizations in the region focused on science education and outreach with instructions where to find and print more copies.

The Co-PIs on this project have also recruited a new postdoctoral researcher, in collaboration with the Apalachicola Bay Systems Initiative at FSU's Coastal and Marine Laboratory (https://marinelab.fsu.edu/absi/) to build on aspects of this research, starting in August 2022. The postdoc will be examining ecosystem service delivery from oyster reefs in the Apalachicola region, including potentially assessing tradeoffs in service outcomes from oyster farms versus restored oyster reefs. The frameworks we have developed in this project for ecosystem service metrics and spatial models of service delivery will provide a critical foundation for this new research.

6.4. Have you developed new collaborations or partnerships (formal or informal) as a result of this work? If yes, please describe the new collaborations or partnerships. *

Yes, although opportunities for new partnerships and collaborations have been constrained by the COVID-19 pandemic (e.g., many people are behind on work deliverables and reluctant to engage in new collaborations; opportunities for in person interaction have been limited), we have developed some new relationships as a result of this work that we hope will be fruitful in the future:

1) We developed a relationship with Dr. Jim Fourqurean's Lab at Florida International University; we sent our carbon samples to Dr. Fourqurean's Seagrass Ecosystems Research lab for carbon analysis, collaborated with him and his staff on testing alternative carbon analysis methods, and are excited to have this new connection.

2) PI Lester has developed a collaboration with Dr. Mariana Fuentes (sea turtle scientist at FSU) and several social scientists (Dr. Lisa Campbell, Dr. Noelle Boucquey) to examine the interactions between seagrass ecosystems, bay scallop populations, green sea turtles, and recreational scallop fishers. Dr. Lester's role in this collaboration was a result of the seagrass expertise she gained from this project. This team currently has a proposal under review at NSF.

3) PIs Lester and Rassweiler have established a collaboration with Dr. Sandra Brooke and the Apalachicola Bay Systems Initiative at FSU's Coastal and Marine Laboratory (https://marinelab.fsu.edu/absi/) to better understand the social-ecological dynamics of the Bay and ongoing restoration work there. They intend to bring the ecosystem service expertise and perspectives they have gained from this project to this new collaboration.

6.5. What, if any, positive changes in policy or practice do you foresee as a result of your work? *

Our project will improve management and conservation of seagrass beds in the Gulf of Mexico. Specifically, the models we have developed will allow for restoration funds and conservation resources to be allocated more strategically for better outcomes, without increasing monitoring costs. Seagrass beds are important habitats that support biodiversity and a range of ecosystem services that benefit society. But these benefits vary across space, such that developing spatial models of this variability can allow restoration and protection efforts to focus on locations that maximize ecosystem service benefits. Our models and research results will also provide tools for more clearly and effectively communicating the diverse benefits of seagrass beds to managers, decision-makers, and the general public.

6.6. If you could make one recommendation to the Gulf Research Program for how best to build on the work you conducted in this project, what would it be? *

Our work had a number of general findings that suggest ripe areas for future research and application. Those findings include: 1) ecosystem services from coastal marine systems show considerable spatial variability and this variability is service-specific (e.g., services show different spatial patterns), 2) climate change impacts like sea level rise will have impacts not just on nearshore marine ecosystems, but also on the benefits that society depends on from those systems (i.e., ecosystem services), and 3) when accounting for future expectations, conservation of existing habitats may sometimes yield more valuable outcomes than restoring lost habitats. These findings suggest that the Gulf Research Program may want to invest in the following research and practice areas:

- Climate change assessments that account for diverse climate drivers (temperature, acidity, sea level, etc.).

- Coupled social-ecological research that accounts for how climate change and management will impact natural systems and ecosystem service provisioning from those systems.

- Social science research that seeks to better understand how coastal communities along the Gulf coast value and depend on different ecosystem services. In our work, we assessed value often in more biophysical terms because of limited data on social values.

- Development of decision support tools to assist managers and restoration practitioners in project site selection, including spatial prioritization tools for selecting marine ecosystem restoration and conservation locations under different climate change scenarios.

7. Communication and Dissemination

Before the form is completed, you may click "Save & Continue Editing" at the bottom of the page at any time to save your work or "Next" to move onto the next page of this form.

When the form is completed, you may click "Mark as Complete" at the bottom of the page to save your work and return to the dashboard.

** denotes required fields*

Note to Grantees: In Section 7, we ask you to help us communicate the importance, progress, and accomplishments of your work. Information provided in this section will be used by the Gulf Research Program to highlight its funded projects in print and electronic informational and promotional materials. The intended audience for the information provided in this section is different and should be thought of as a general audience. When you return to the dashboard, you may upload images that represent and illustrate the work of your project.

7.1. Please describe the most exciting or surprising thing you have learned while working on this project in a way that is understandable by a general audience. *

Our work was initially focused on understanding the benefits of seagrass restoration. We sought to address the question of what would be gained from seagrass restoration in terms of healthier ecosystems, more productive fisheries, better protected coastlines, slower climate change, and other valuable outcomes. While we found that seagrass restoration would lead to all these benefits, we were surprised to find that conserving existing seagrass beds was often even more important than restoring those that have been lost. Because the beds that remain are often in the most favorable locations for dense seagrass, they are particularly good at providing benefits to people. It is crucial then, that we balance both goals as we care for Florida's coastal environment: preserving existing seagrass beds, while restoring beds that have been lost where possible.

7.2. Do you have any stories that capture the impact of this project? (optional)

If so, please share one or two. Examples of what we are interested in include stories of people/communities that the project has helped; lives that have changed; work that led to policy change, such as legislation or regulation; and research breakthroughs.

No.

7.3. Have any communications, outreach, or dissemination activities occurred in relation to your project?*

Please describe:

- Any press releases issued (other than that issued by the National Academies of Sciences, Engineering, and Medicine) about the project.
- Any media coverage or news stories about the project.
- Any social media accounts, websites, listservs, or other communication vehicles used to communicate information about this project. Please include relevant web addresses if available.

We have been working to synthesize our project results into usable products and recommendations for seagrass monitoring, management and restoration aimed at both practitioners and researchers, in addition to the general public. These dissemination efforts include:

1) Fact sheets intended for dissemination to the general public, managers, and restoration practitioners: We have developed several 2 page fact sheets, and are currently finalizing the content in these handouts. We have secured the equipment and materials to print and distribute hard copies after the conclusion of the grant, and will also provide electronic copies on our project website (https://www.lester-lab.com/seagrass). We have developed the following fact sheets:
- Geographic variation in seagrass ecosystem services: This sheet explains the concept of seagrass ecosystem services; explains how services can show important geographic variation; discusses challenges with direct empirical monitoring of ecosystem service outcomes of seagrass restoration and management; introduces the spatial ecosystem service models we have developed in this project as a potentially convenient alternative to direct monitoring; and highlights some of the hot spots for different seagrass services along the Florida Gulf Coast.

- Geographic variation in seagrass ecosystem services - Regional summaries: These fact sheets cover similar content to the previously described fact sheet, but with a focus on a specific region within Florida, in the hopes that more targeted information would be more useful to some end-users. We are developing regional summaries for Northwest, North Central, Northeast, Southwest, and South Florida, and these versions include information about service hotspots on a finer spatial scale and data on the status of seagrass beds within each region.

- Modeling seagrass ecosystem services: This sheet explains, for a non-technical audience, the benefits of developing spatial models of ecosystem services. It features a table with a row for each seagrass service (biodiversity enhancement, carbon storage, recreation, coastal protection, nursery habitat) and the following columns: the importance of the service, the metrics that can be used to monitor the service, methods for measuring the service empirically, and how accurately the service can be modeled.

2) Social media: Project PIs Drs. Sarah Lester and Andrew Rassweiler have a joint lab twitter account (@RassterLab; >500 followers) and Instagram account (@rassterlab; >250 followers) and both have been used to communicate project activities, primarily focused around field work (although neither account is exclusive to this project). We ran a social media campaign in 2020 called #SeagrassSaturdays where project team members posted fun facts, videos, and photos on the lab Instagram to raise awareness about this project, as well as the ecology, threats, restoration potential, and scientific process of studying seagrass systems. Jenn McHenry (the PhD student on the project) also has an instagram account (@Salty_Biogeography; >100 follower) aimed at communicating project activities, engaging the public in her research, and creating greater awareness for the value and vulnerability of coastal ecosystems like seagrass beds.

3) Conference presentations:
- "Modeling the biodiversity enhancement value of seagrass beds," The International Biogeography Society, Annual Meeting, In-person presentation.

- "Modeling the biodiversity enhancement value of seagrass beds", Geo Hab: Marine Geological and Biological Habitat Mapping Conference, Virtual Talk, 2021
- "Geographic variation in carbon storage by Florida seagrass beds," American Association of Geographers Annual Meeting, Virtual Poster, 2021

4) R Shiny package for results from seagrass distribution and biodiversity enhancement paper: http://jennifermchenry.shinyapps.io/seagrass_bev

5) Project Website: https://www.lester-lab.com/seagrass

6) Data and model code access: We are also archiving all project data and model code and making them fully publicly available, ensuring discoverability and accessibility, following manuscript publication or within no more than two years of end of grant period, whichever comes first. See data management reporting section for more details.