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Advancing consistent socio-economic monitoring of coastal ecosystem restoration through collaborative metric development

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Ecological restoration programs increasingly aim to provide socio-economic and environmental benefits. However, monitoring of socio-economic outcomes of these programs lags behind monitoring of ecological outcomes. Socio-economic methods are less established, managers have less experience, and metrics used vary, stymieing evaluation and adaptive management. Here we demonstrate that logic models and stakeholder engagement can be used to identify core socio-economic metrics across various types of restoration, focusing on coastal restoration in the Gulf of Mexico. Across four major restoration types (oyster restoration, habitat restoration, recreation enhancement, and water quality improvement), core metrics were identified as changes in jobs, restoration expenditures, recreational activity, cognitive function, and subjective well-being. These metrics can provide a starting point for increased and more consistent monitoring of socio-economic outcomes. The collaborative, science-based, and replicable process we developed to identify core metrics can be applied to other ecosystems and management actions to expand monitoring and evaluation of socio-economic impacts.

From global to local scales, natural resource programs and policies increasingly support ecological restoration to achieve socio-economic and environmental goals. Common socio-economic goals include community resilience, economic prosperity, supporting social and community values, public health, risk reduction, hazard mitigation, and other aspects of human well-being[1–3]. The combination of environmental and social goals is reflected in the United Nations Sustainable Development Goals which integrate environmental and human development goals, recognizing their tight interdependence[4,5]. The public health community is also rapidly expanding its understanding of environmental determinants of health[6,7] and is calling for more integrated approaches to pandemic and disease prevention that encompass environmental drivers[8–10]. Yet, this shift toward integrated goals, missions, and policies to achieve human well-being outcomes is not yet reflected in restoration program development, implementation, and monitoring[3].

Here, we focus on monitoring as a best practice for determining whether restoration efforts are effective, enabling adaptive management, and informing other restoration efforts[11]. In decades past, restoration has been motivated by ecological goals, so restoration design and monitoring has primarily focused on environmental outcomes. More recently, some restoration programs are shifting to a broader socio-economic framing, For example, the Gold Standard and the Global Environment Facility Forest and Landscape Restoration program have developed targets and metrics that incorporate environmental and socio-economic outcomes[12,13]. International principles and standards for the practice of ecological restoration explicitly state that effective implementation "contributes to protecting biodiversity; improving human health and well-being; increasing food and water security; delivering goods, services, and economic prosperity; and supporting climate change mitigation, resilience, and adaptation"[14]. However, this inclusion of socio-economic goals has not been met by sufficient

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development of methods and metrics for designing and monitoring restoration programs or projects for socio-economic outcomes[15–17].

One of the largest restoration programs in the United States is coordinated between the federal government and state programs in the Gulf of Mexico and aims to achieve both ecological and socio-economic goals. Gulf Coast habitats are diverse, and include beaches and dunes, coastal marshes, oyster reefs, and seagrass beds[18]. Natural resources underpin major sectors of the economy in the region, with millions of people participating in wildlife-based tourism that generates billions of dollars in annual spending and tax revenues[19,20]. However, the socio-economic context of the Gulf is defined by historical inequities, relatively high poverty rates, and low economic mobility. This leaves many communities especially vulnerable to disasters[21]. The Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act of 2012 directed around USD 5 billion to restore coastal habitats, communities, and economies after the damage incurred by the Deepwater Horizon Oil Spill[22]. Five goals have been set to guide this funding: (1) Restore and Conserve Habitat; (2) Restore Water Quality and Quantity; (3) Replenish and Protect Living Coastal and Marine Resources; (4) Enhance Community Resilience; and (5) Restore and Revitalize the Gulf Economy[23]. While several of these goals focus on socio-economic outcomes, monitoring of outcomes from RESTORE-funded projects initially concentrated on their ecological effects. The RESTORE program has identified over 50 metrics for monitoring, the majority of which measure ecological outcomes; socio-economic metrics focus on the number of people engaged with the project (e.g., as volunteers, through training, or as visitors to a site), the number of jobs created, and number of facilities benefitting from a community resilience project[24]. The RESTORE program aims to use monitoring and evaluation results to inform decision-making for current and future projects[25]. When this project was initiated, the RESTORE program was interested in expanding monitoring to encompass a broader suite of socio-economic benefits[26].

To help expand monitoring of socio-economic benefits, we conducted the Gulf of Mexico Ecosystem Service Logic Models & Socio-Economic Indicators Project (GEMS) in collaboration with relevant funders (e.g., RESTORE, National Fish and Wildlife Foundation, states), experts, and practitioners across the Gulf. Our primary objectives were to (1) identify the main socio-economic outcomes of common restoration practices used in the Gulf of Mexico and (2) to develop a set of feasible and useful metrics for monitoring these socio-economic outcomes. The metrics account for current constraints in data and methods and were developed with restoration practitioners and experts from diverse disciplinary perspectives. These core metrics reinforce some existing RESTORE program metrics, and go beyond them, identifying metrics that could be adopted to more fully characterize the stated socio-economic restoration goals of the RESTORE program.

Results

Ecosystem service logic models and socio-economic outcomes

A total of 23 ecosystem service logic models (ESLMs) were developed, one for each restoration project type (Table 1).

ESLMs show how each restoration action cascades through both natural and human systems to result in a set of directly linked socio-economic outcomes[27–34] (Fig. 1). We define outcomes as types of impact that restoration projects can have (e.g., economic impact, provision of cultural value, property protection), while metrics are specific measures that could be used to monitor particular aspects of each outcome (e.g., number of jobs provided, changes in cognitive function resulting from time spent at the project site, number of homes with reduced coastal erosion) to determine if the restoration project yielded a change in the outcome. The full set of ESLMs is available online[35].

The ESLMs indicate that two outcomes are likely to be affected by all types of coastal restoration assessed: economic activity associated with implementation of the project, and knowledge outcomes (when education programming is included). Other outcomes are expected from the majority of restoration types assessed, including recreational fishing opportunities, recreation-associated economic activity, subsistence harvest, climate stabilization (carbon sequestration), and property protection (via reduction of erosion). Recreational enhancement projects and water quality improvement projects are expected to affect fewer and different outcomes than other restoration types. For example, recreational enhancement projects are not expected to affect climate stabilization and are likely to influence property value (through real estate value) rather than property protection (through erosion reduction). Water quality improvement approaches are likely to affect socio-economic outcomes related to the targeted water body rather than the project site, leading to more regional effects including changes in water-associated health impacts and costs associated with drinking water and wastewater treatment.

The development of the ESLMs clarified a number of distinguishing features of specific project types that influence the socio-economic outcomes they create, and therefore which metrics are relevant to monitor. For example, Fig. 2 shows ESLMs for two different types of oyster reef restoration: a cultch plant intended to generate oysters for harvest and a living shoreline that uses oysters to build intertidal habitat. The differences in the structural complexity of these two types of oyster reef restoration and whether the reef is periodically set back by intensive harvest influence the outcomes created by these types of projects. As the ESLMs show, the cultch plant supports commercial oyster harvest, creating jobs and revenue[36], and is likely to support local food security and cultural values including sense of place by preserving traditional livelihoods. In contrast, living shoreline type oyster reefs in intertidal settings are not intensively harvested due to the smaller size of oysters on those reefs[37], so do not create outcomes related to commercial oyster harvest. However, the living shoreline reefs develop structural complexity that improves fish habitat[38] and contributes to wave attenuation and shoreline protection[39]

While we compare and elaborate on outcomes of two example restoration strategies in this section, the ESLMs, associated context documents, and project reports[35,40,41] provide additional detail about how each of the 23 restoration project types is expected to affect the associated outcomes and indicate what design decisions and external factors influence those outcomes.

Metrics

For the 23 restoration approaches assessed, we identified 44 metrics that could show changes in outcomes resulting from restoration investments

Table 1 | Project types included in the Gulf of Mexico Ecosystem Service Logic Models & Socio-Economic Indicators Project

Habitat restoration	Oyster reef restoration	Recreation enhancement	Water quality improvement
• Salt marsh • Seagrass • Mangrove • Living shoreline • Beach & dune • Hydrologic connectivity • Oyster reef (general)	• Simple subtidal, intensively harvested • Complex subtidal, intensively harvested • Complex subtidal, not intensively harvested • Complex intertidal, not intensively harvested • Protection or enhancement • Aquaculture	• Boat ramps • Fishing piers • Trails and boardwalks	• Sewage system improvements • Wastewater treatment plant upgrades • Treatment wetlands • Stormwater management—gray infrastructure • Stormwater management—green infrastructure • Stormwater management—outflow treatment • Agricultural best management practices

Oyster reef restoration was included as one project type in the habitat restoration category, but also served as its own category with six more specific types of oyster reef restoration projects. See "Methods" for detail on how project types were selected.

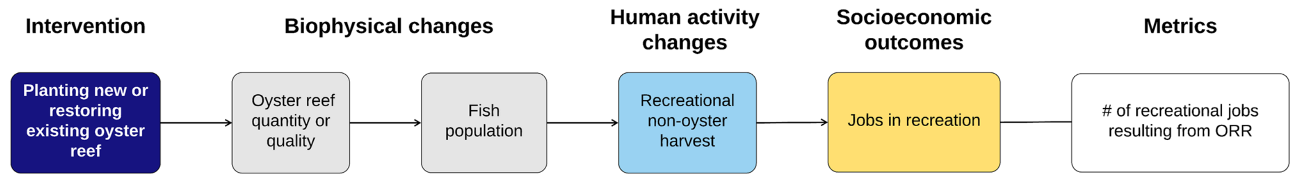

Fig. 1 | Simplified ecosystem service logic model example. This example pathway from an ecosystem service logic model shows how a restoration action leads to a socio-economic outcome, and what metric could be used to measure that outcome. Ecosystem service logic models are made up of multiple pathways to show the variety of outcomes created by a restoration action.

(see Supplementary Table 3 for full metrics list)[35]. Eight of these were classified as Tier 1 metrics, meaning that they are considered feasible for measurement by non-expert teams. Twenty-four metrics were classified as Tier 2, which would require additional expertise and resources to monitor, and the remaining 12 are research & development (R&D) metrics, with additional research and methods development required to enable their measurement. Across all metrics, the majority (35 metrics) quantify project-scale processes that could be observed or monitored at project sites. These will be the easiest to integrate into restoration project implementation because they do not require coordination across multiple projects and in many cases can be incorporated into routine project monitoring. Some outcomes, like economic activity, can be measured at both project and regional scales due to the availability of both local- and regional-scale datasets or methods. Quantifying regional-scale metrics would require investments beyond project-scale monitoring, either to aggregate data from multiple projects or to conduct larger-scale modeling and/or extrapolation. Thirty-eight of the 44 metrics identified are not currently required in the Gulf of Mexico restoration programs such as RESTORE Observational Data Plan guidelines[24] or the National Resource Damage Assessment Monitoring and Adaptive Management Manual[25], and thus could complement existing reporting to more fully represent socio-economic outcomes of restoration (see Supplementary Table 3 for overlap with RESTORE and National Resource Damage Assessment metrics).

We termed metrics relevant to at least half of the restoration approaches assessed in a given restoration category "core metrics." We identified a set of 18 core metrics (13 at the project scale, five at the regional scale) that measure outcomes that are strongly linked to multiple project types (Tables 2 and 3) and that can be measured with current data and methods (i.e., are not R&D metrics). We consider project types and metrics strongly linked when a specific project type is highly likely to influence the metric, as determined by our literature review and expert consultations.

Given the state of data and methods in the region, two of the project scale core metrics (number of restoration jobs supported by the project and restoration expenditures by the project) were considered feasible for measurement by non-expert teams (i.e., Tier 1). These metrics provide a practical starting point for immediate wider adoption, as they relate to socio-economic outcomes expected for multiple restoration approaches and can be collected with relatively little expertise and resources. An additional 16 core metrics are relevant to common coastal restoration approaches and could be monitored with relevant expertise and sufficient resources (i.e., Tier 2).

A number of metrics are strongly linked to multiple different restoration approaches, presenting opportunities for comparison across restoration categories and aggregation of effects across multiple projects. At the project scale, five core metrics were identified as relevant to all restoration categories assessed: number of restoration jobs supported by project, restoration expenditures by the project, change in recreational activity expenditures associated with project site visitation, change in cognitive function, and change in subjective well-being (Table 2). Monitoring of these metrics would likely be relevant for any restoration approach assessed.

Six additional project scale core metrics were relevant to the majority of oyster restoration, habitat restoration and recreation investments, but not to water quality improvement projects. These metrics tend to be linked to habitat enhancement and people's ability to visit project sites, which the water quality improvement projects do not usually provide as they focus on gray infrastructure improvements (e.g., to wastewater treatment plants or septic systems). The core metrics for habitat related projects quantify changes in the number of people with knowledge of the habitat or project outcomes, recreational fishing jobs and expenditures, food security, and property protection. Four of the core project scale metrics had counterparts identified at the regional scale, suggesting that investments in evaluating these outcomes at both scales could be informative (Table 3). One core metric can only be assessed at the regional scale, given current data. That metric is focused on economic expenditures related to commercial fishing and is most relevant to habitat and oyster restoration investments.

Discussion

We identified a set of core socio-economic metrics that are likely to be relevant to a wide range of coastal restoration approaches in the Gulf of Mexico. The stakeholder engagement and ESLM development processes conducted by this project reinforce that restoration investments in this region are likely to have socio-economic effects, and that a consistent set of metrics can be used for monitoring those effects. The metrics and ESLMs developed through this process can provide a starting point for research and management teams designing socio-economic monitoring. Not all metrics may be relevant in each specific context, but when consistent metrics can be adopted, they are likely to improve uniformity and efficiency in monitoring and evaluation of the major types of coastal restoration receiving investments across the Gulf region. Using a common set of metrics on social and economic outcomes allows comparison of effectiveness across projects, as well as better evaluation of regional impact of restoration on social, economic, and community recovery in regions impacted by the Deepwater Horizon Oil Spill and other shocks like hurricanes.

The measurement protocols developed for each of the core metrics are designed to guide consistent and high-quality measurement of many of the socio-economic metrics identified through the GEMS process[35,42]. Many of the socio-economic metrics identified through this process can be measured using established methods (e.g., intercept surveys[43], erosion monitoring[44], property valuation[45], mental health surveys[46], social cost of carbon[47]) which are included in available measurement protocols and are ready for use[42]. There are, however, still a number of needs to be addressed for consistent and widespread measurement of socio-economic outcomes of restoration projects.

One need relates to attributing change in an outcome to a project or set of projects. Both the literature review and expert consultation confirmed that the change in an outcome created by a specific restoration project, or even a set of projects, can be too small to detect relative to all of the other factors that influence that outcome. Causal methods such as use of a control site[44] or hedonic regression[45] can be used to better attribute a change in certain outcomes to a restoration activity, but they require additional expertise and resources. Measurement of restoration impacts could also be improved by making more relevant data publicly accessible in a useful format. Some datasets are aggregated to large geographic areas that obscure project impacts, while others are not publicly accessible and may be difficult or impossible to obtain or do not capture the entire relevant outcome. As the set of R&D metrics indicates, there remains a need to further develop some methodologies for measuring outcomes (see Supplementary Table 3). For example, in the case of water system cost outcomes, experts in our

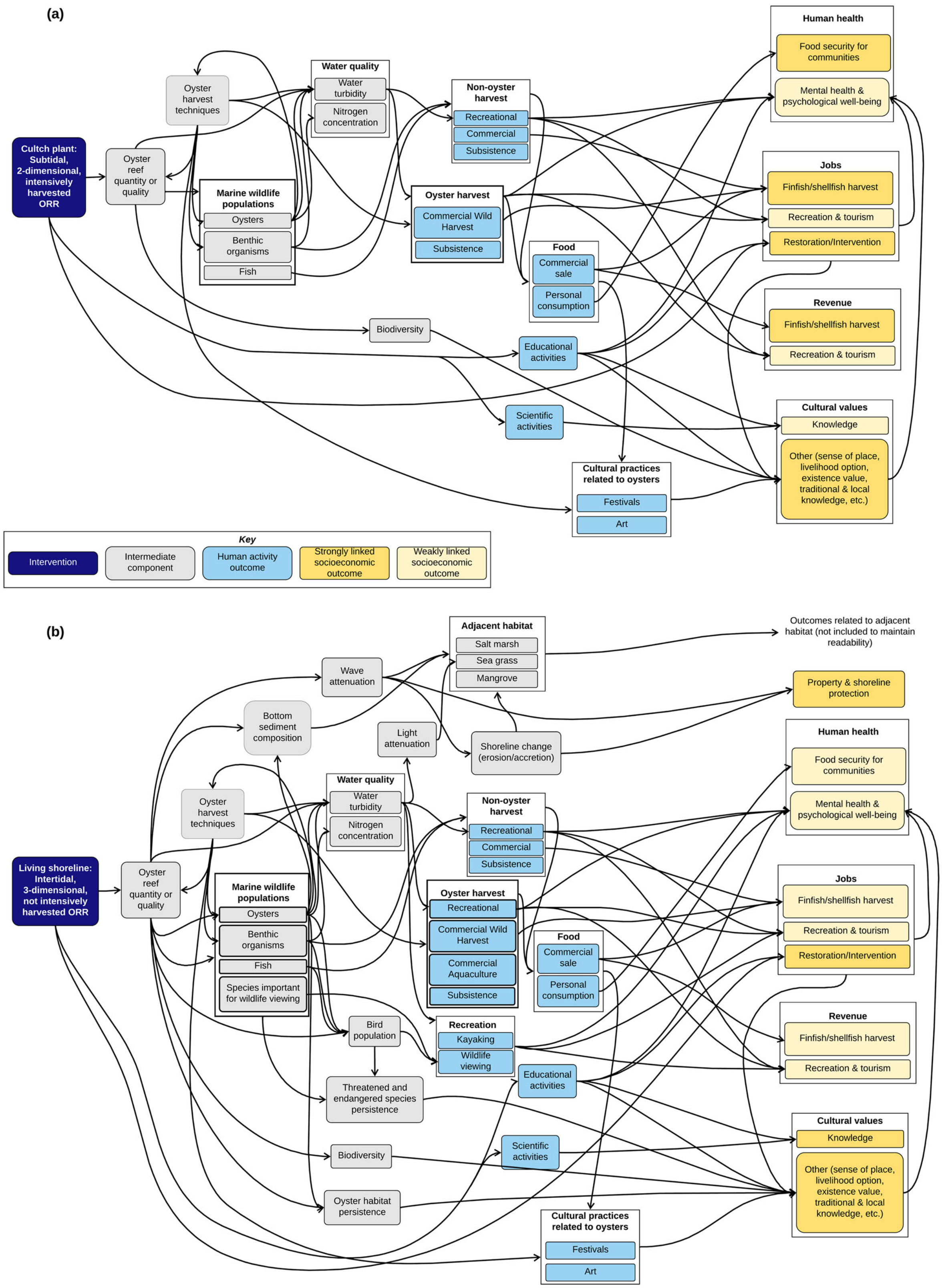

Fig. 2 | Ecosystem service logic models for two different types of oyster restoration projects. a a cultch plant, where oyster shells are placed subtidally to create a two-dimensional structure on which oysters grow until they are harvested using intensive methods such as dredging, and (**b**) a living shoreline, where three-dimensional structures are placed in the intertidal zone to allow oyster colonization and long-term growth without harvest.

Table 2 | Project scale core Gulf of Mexico Ecosystem Service Logic Models & Socio-Economic Indicators Project metrics

Outcome	Metric	Tier	Habitat restoration (7 project types)	Oyster restoration (6 project types)	Recreational enhancement (3 project types)	Water quality improvement (7 project types)
Core metrics common across all categories and project types						
Economic activity: restoration/ intervention	Number of restoration jobs supported by project	1	7[a]	6[a]	3[a]	7[a]
	Restoration expenditures by project	1	7[a]	6[a]	3[a]	7[a]
Core metrics common across all project categories						
Economic activity: recreation and tourism	Change in recreational activity expenditures associated with project site visitation	2	5[a]	3[a]	2[a]	4[a]
Human health: Mental health & psychological well-being	Change in cognitive function	2	5[a]	3[a]	3[a]	4[a]
	Change in subjective well-being	2	5[a]	3[a]	3[a]	4[a]
Additional core metrics for specific project categories						
Cultural values: knowledge	Education-related knowledge: Number of people with additional knowledge of habitat effects and other project outcomes	2	6[a]	3[a]	2[a]	3
	Awareness: Number of people with additional knowledge of habitat effects and other project outcomes based on project site	2	6[a]	3[a]	2[a]	3
Cultural values: other	Project identified cultural value	2	5[a]	6[a]	3[a]	2
Economic activity: recreation and tourism	Number of jobs supported through recreational fishing at project site	2	5[a]	3[a]	2[a]	2
	Change in recreational fishing expenditures associated with project site visitation	2	5[a]	3[a]	2[a]	2
Human health: food security for communities	Proportion of surveyed harvesters who say that food caught/harvested at the site is important for feeding their household	2	4[a]	4[a]	3[a]	1
Property protection	Amount of property adjacent to shoreline with reduced erosion after project	2	5[a]	3[a]	0	0
Property value	Change in property value across affected properties	2	3	0	3[a]	3

The four right-hand columns (one for each project category) indicate the number of individual project types within that category that are strongly linked to the metric, meaning that the project type is expected to meaningfully influence the metric.
[a]the metric is strongly linked to at least half of the project types within the project category and is considered a core metric for that category.

Table 3 | Regional scale core Gulf of Mexico Ecosystem Service Logic Models & Socio-Economic Indicators Project metrics

Outcome	Metric	Tier	Habitat restoration (7 project types)	Oyster restoration (6 project types)	Recreational enhancement (3 project types)	Water quality improvement (7 project types)
Common across all project types and categories						
Economic activity: restoration/intervention	Change in economic activity from restoration spending	2	7[a]	6[a]	3[a]	7[a]
Additional metrics for specific project categories						
Cultural values: knowledge	Awareness: number of people with additional knowledge of habitat effects and other project outcomes on broader scale.	2	6[a]	3[a]	2[a]	3[a]
Cultural values: other	Program-identified cultural value	2	5[a]	6[a]	3[a]	2[a]
Economic activity: recreation and tourism	Change in economic activity from recreational fishing	2	5[a]	3[a]	2[a]	2[a]
Economic activity: finfish/shellfish harvest	Change in economic activity from project-associated commercial fish harvest	2	4[a]	3[a]	0	2[a]

The four right-hand columns (one for each project category) indicate the number of individual project types within that category that are strongly linked to the regional scale metric, meaning that the project type is expected to meaningfully influence the metric.
[a]the metric is strongly linked to at least half of the project types within the project category and is considered a core metric for that category.

workshops suggested that relevant data are being collected by individual water utilities, but these data have not been evaluated for the effect of restoration projects on water system costs. For other outcomes, such as food security from subsistence harvest, there are examples of measurement at small scales through surveys[48], but not for measuring impacts on a larger scale that can be attributed to a restoration project. As restoration monitoring and evaluation has historically focused on ecological outcomes, there is a need to enhance social science skills or better connect social scientists to restoration monitoring. Many of the core metrics identified are commonly monitored through methods that require engagement with communities and often depend on trusted relationships (e.g., for administering surveys, focus groups or interviews). Enhanced efforts to develop these relationships or connect people with these relationships to restoration monitoring efforts will be needed. See Supplementary Discussion for more details on these challenges.

All of the Tier 1 (easy-to-measure) metrics are project scale, which suggests that understanding regional effects of restoration actions is likely to require investments beyond commonly implemented monitoring. For example, additional primary data collection across multiple projects or modeling efforts to extract attributable effects from regularly reported regional statistics (e.g., for commercial fishery revenues) would help to fill gaps in regional understanding. Many of these analyses have been done in different regions across the Gulf (e.g., refs. 49–52,), but not at a scale or frequency for evaluating many of the restoration investments being made in the region. Support from and partnership with federal agencies, universities, or other parties are likely needed to enable regional or program-scale impact evaluation of restoration efforts.

Without additional investment in measuring socio-economic outcomes of restoration projects, both by individual projects and at larger scales, the effects of these projects on many outcomes, such as physical health, mental well-being, and food security, cannot be fully understood and incorporated into project planning and design. If these outcomes are more consistently measured, we will gain a broader understanding of the effects of restoration, and project planners can more easily consider these potential outcomes from the outset, resulting in projects that create a broader suite of benefits for people and ecosystems. Documenting these socio-economic outcomes could also build the evidence base for a diverse set of outcomes, giving a wider range of funders confidence that investments in restoration may contribute to the health, social, and economic well-being of communities.

Conclusions

Funders, policymakers, and affected communities are increasingly interested in the socio-economic outcomes of environmental interventions. We provide a consistent and community-vetted starting point for monitoring restoration effects on socio-economic outcomes in the Gulf of Mexico. To our knowledge, this is the first large-scale, evidence-based, and consensus-driven effort to identify socio-economic metrics for monitoring of coastal restoration in the Gulf of Mexico. The method used to identify these metrics is replicable, provides a means to draw on diverse disciplines and expertise to identify common, stakeholder-relevant socio-economic metrics, and has resulted in clear opportunities to advance monitoring of socio-economic outcomes, such as:

1. Expanding project monitoring of socio-economic outcomes by broadening each project's current set of metrics. While the Tier 1 metrics (Table 2) require few additional resources to measure and provide an accessible starting point, Tier 2 metrics are also within the reach of many projects and can be considered for measurement. The GEMS metrics protocols provide guidance on measurement methods, including methods for assessing equity effects through analysis of the distribution of the measured outcome among different groups of people. Uptake of these metrics could be accelerated if funders or regulators required or recommended their use.
2. Testing measurement protocols to further advance methods. Testing measurement and distribution protocols will help to refine the

measurement methodologies, clarify the costs and time required for measurement, and illustrate the utility of the data collected for tracking the impact of restoration projects on social outcomes, economic well-being, and equity.
3. Developing data and methods for R&D metrics. More comprehensive monitoring of socio-economic outcomes will require expansion of data collection, creative use of existing data, and new analytical applications. These will need to be supported at both the project and the regional scales.
4. Investing in measurement of regional scale metrics. Most restoration teams will not have the capacity or resources to conduct monitoring needed to assess regional-scale outcomes. Funding programs, universities, and non-profits could invest in and conduct studies to evaluate regional scale economic, water quality and health impacts of restoration investments, building on those already underway in a few regions.

The growth in restoration investments and the expansion of restoration goals to include socio-economic outcomes has created a need for efficient and effective monitoring of these outcomes. The development and use of the core metrics like those identified through the GEMS process can provide much needed consistency and efficiency across multiple types of restoration investments. Broad replication of the methods developed here and adoption of core metrics is highly relevant to existing large-scale restoration programs (e.g., RESTORE) and new efforts being developed through investments in ecosystem restoration[53,54], nature-based solutions[55,56], and systems of national natural capital accounting[57,58].

Methods

General approach for developing generalized logic models and common metrics

We identified socio-economic outcomes and metrics for coastal restoration in the Gulf of Mexico through a collaborative process with an advisory council, which provided high-level guidance throughout the project, and a group of restoration practitioners, researchers, and community members who participated in workshops, calls, or focus groups (see Supplementary Notes 1 and Supplementary Tables 1–2 for details). This involved seven in-person workshops (at least one in each Gulf Coast state), four virtual workshops, and one-on-one calls and focus groups with over 80 scientists and practitioners. In total, 62 distinct organizations were engaged (Supplementary Note 1 and Supplementary Table 1). As described below, this was an iterative process in which the project team repeatedly sought input and feedback from experts and stakeholders on draft versions of the socio-economic outcomes and metrics lists.

The restoration approaches included in this project were chosen based on input from the advisory council and published strategy and planning documents for the RESTORE program[59–61] (M. Love, pers. comm.). The logic model development and metric selection methods described below were piloted and fine-tuned on six types of oyster reef restoration (simple subtidal harvested, complex subtidal harvested, complex subtidal, complex intertidal, protection or enhancement of existing reef, and aquaculture). Oyster reef restoration was selected as the focus for the pilot with input from the GEMS advisory council due to its widespread use throughout the region, economic importance, and the large body of scientific research available to support development of ecosystem service logic models and socio-economic metrics. The method was then applied to the remaining restoration approaches which were grouped into three categories: habitat restoration and conservation (salt marsh, seagrass, mangrove, living shorelines, beaches and dunes, and hydrologic connectivity), recreational enhancement (boat ramps, fishing piers, and trails and boardwalks), and water quality improvement (sewage system improvements, wastewater treatment plant upgrades, treatment wetlands, and stormwater management improvements using gray or green infrastructure). More detailed descriptions of each of these project types can be found on our project website[62]. Through April 2023, 67% of environmental restoration projects funded by RESTORE included one of the GEMS project types[63].

Working with participants, we first identified common socio-economic outcomes expected from the most common types of restoration using collaboratively developed ecosystem service logic models (ESLMs). The participants then identified possible metrics for the socio-economic outcomes and screened them for practicality based on data and measurement constraints.

Ecosystem service logic model development & metric identification

Draft ESLMs connecting restoration activities to socio-economic outcomes were created for six different types of oyster reef restoration, using a combination of literature (e.g., refs. 38,64,65) and expert input. We held a series of workshops with restoration practitioners, researchers, and stakeholders to refine the ESLMs in five focal estuaries (one in each Gulf Coast state to reflect various socio-ecological conditions found across the Gulf – Galveston Bay, TX; Chandeleur-Breton Sound, LA; Back Bay of Biloxi, MS; Mobile Bay, AL; and Charlotte Harbor, FL; see Supplementary Table 1 for participant details). Draft logic models were iterated with participants to ensure they reflected the full range of oyster reef restoration approaches and outcomes in each focal estuary. Participants also created an initial list of socio-economic metrics that could be used to measure outcomes that were specified through the logic models (workshop details available[40]). Not all relevant areas of expertise were represented by workshop participants, so additional, targeted outreach was conducted with individuals to fill gaps (see Supplementary Notes 2 for interview protocol).

Refinements to the oyster restoration ecosystem service logic models and metrics were verified through a review of both peer-reviewed literature and white papers. Some metrics suggested at the workshops were refined based on information from the literature[66]. To finalize the metrics list, we held a regional workshop including representatives from each local workshop, additional experts on oyster reef restoration and socio-economic indicators, and members of Gulf Coast restoration funding organizations (see Supplementary Table 1 for participant details)[40]. Regional workshop participants screened the metrics using the SMART criteria[67] (specific, measurable, achievable, realistic, and time-bound), with a focus on the feasibility and relevance of each proposed metric, availability of existing data, and scale of application (whether metrics could be measured by individual projects or at a larger program scale).

Following the oyster reef restoration pilot, the GEMS advisory council requested that this project be expanded to include all ecosystem restoration approaches commonly used in the Gulf of Mexico. This was a broader scope than had been originally planned, which required us to streamline the process used for identification of metrics for oyster reef restoration to allow us to develop metrics for the other major restoration approaches within the time and resources allocated for this project. We did so using learnings from the pilot phase. Additionally, adjustments were made to move engagements online during the height of the COVID pandemic. One key insight from the oyster reef restoration pilot was that many ecosystem restoration approaches have similar effects on the biophysical and ecological systems, which translate into similar changes to human activity and socio-economic outcomes. For example, some of the key ecological outcomes of oyster reef restoration are improved water quality, reduced shoreline erosion, and enhanced populations of estuarine and marine wildlife. These changes support socio-economic outcomes such as recreational and commercial seafood harvest, other recreational activities, and protection of property and infrastructure. Many of the additional restoration approaches to be included in the GEMS project were other habitat types that have overlapping ecological and socio-economic outcomes with the oyster reef restoration approaches, enabling us to build on the ESLMs and metric results from the pilot phase.

Therefore, we used a condensed collaboration process to develop ESLMs and metrics lists for ecological restoration approaches that have similar ecological effects as oyster reef restoration (salt marsh restoration, seagrass restoration, mangrove restoration, living shorelines, beach and dune restoration, and hydrologic connectivity restoration) and for recreational enhancement projects with more similar effects on human activity (boat ramps, fishing piers, and trails and boardwalks). We drafted ESLMs and metrics lists for each of these restoration approaches, using the resources developed for the oyster reef restoration pilot as a starting point. Then, we used an iterative series of individual and small-group virtual meetings to gather input from experts on the ESLMs and metrics, consulting at least two experts for each ESLM created in this phase of work (e.g., salt marsh restoration) and at least two additional experts for each new metric (e.g., change in property value).

For water quality improvement projects, which cause substantially different environmental and socio-economic changes than the other restoration approaches included, we used a literature review to draft ESLMs and an initial list of potentially relevant metrics. Then, we held a regional workshop in which experts from across the Gulf region were invited to (1) share feedback on the restoration techniques included for water quality improvement projects, (2) give input on ESLMs, (3) clarify social and economic outcomes, and (4) brainstorm lists of possible metrics. Participants' expertise included public health, water quality, restoration, environmental justice, social science, economics, and natural resource management (see Supplementary Table 1 for participant details).

The updated ESLMs and metrics from the regional workshop were used as the basis for two virtual workshops (one on health outcomes; the other on economic and cost outcomes) engaging experts at local, state, and Gulf wide levels to gather additional input, testing metrics against the SMART criteria with a particular focus on feasibility. Through the expert consultations we also identified which outcomes were most likely to be measurably affected by the water quality improvement projects. Following the workshops, we conducted additional literature review and virtual expert calls to iteratively refine the ESLMs and metrics. Similar to phase 1, workshop participants represented practitioners, affected communities, and experts that work with these communities.

Metric synthesis

Funders and restoration practitioners often seek a common set of metrics that can be meaningfully observed across multiple restoration approaches to allow comparison across projects and aggregation of results for larger regions, and to make efficient use of monitoring funds. To address this need, those metrics that were considered relevant for at least half of the project types in at least one of the categories (habitat restoration, oyster reef restoration, recreational enhancement, and water quality improvement) were labeled as core metrics.

Identified metrics vary in terms of expertise and resources required to monitor them. To reflect this variation, metrics were grouped into three tiers. Tier 1 metrics were defined as requiring relatively low effort and expertise to monitor. Tier 2 metrics were defined as those requiring more specialized expertise and higher levels of resources to monitor. R&D metrics were defined as those that do not yet have well-established methods widely accepted by relevant disciplinary fields.

The collaborative process and literature reviews also revealed that some outcomes can be observed at a project scale as the result of localized changes, while others can only be observed or modeled at a regional scale (e.g., economic impact and water quality) due to their reliance on ecosystem-scale processes, or the scale of available data (e.g., aggregated at the county scale). To indicate this, metrics were specified as either project or regional scale.

Many funders and practitioners are interested in how their projects contribute to community resilience, or communities' capacity to adapt to short- and long-term natural and man-made hazards, particularly increased flood risks associated with sea-level rise and environmental stressors[26]. There is not widespread agreement across disciplines as to what constitutes community resilience, but there is recognition that many different social and economic outcomes contribute to it. We worked with resilience experts to identify a subset of outcomes that likely contribute to community resilience and described our rationale for each (see Supplementary Table 4 for details).

Our Gulf partners were also interested in metrics that could ascertain how restoration projects affect equity, with a particular interest in whether underserved communities might be affected differently and whether the installation of a restoration project worsened or alleviated existing inequities. As any outcome can cause equity effects if distributed unequally among populations, any of the metrics identified could be assessed for distributional effects. For example, in addition to measuring how many restoration jobs were created, one could also assess who is getting those jobs. Similarly, in addition to measuring the number of days evacuation routes are closed, one could assess who is most affected by those closures.

Measurement protocols

To facilitate use of these metrics in project monitoring, we developed measurement protocols for each of the core metrics. Measurement protocols are based on established, previously published methods and aim to provide a sufficient level of detail to guide consistent and high-quality measurement[35,42]. This is especially important as restoration practitioners tasked with monitoring are more likely be trained in natural science methods and have less familiarity regarding the use of social science methods to measure core metrics. Each protocol includes a how much section that describes how to quantify the metric and track if it is changing due to project installation. To address the potential use of any metric for assessing equity effects, we included a who section in each measurement protocol that describes how to evaluate who has access to the outcome the metric is measuring and whether that access is representative of the community around the project. The who protocols are intended to give projects tools to consider the equitable or inequitable distribution of their projects' effects.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The ecosystem service logic models, metrics database, and measurement protocols developed for this study are available in the Duke Research Data Repository[35], https://doi.org/10.7924/r45b0962f. The Deepwater Horizon Project Tracker[63] used to assess how the GEMS project types aligned with funded projects is publicly available at https://dwhprojecttracker.org/.

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Author contributions

Lydia Olander, David Yoskowitz, Chris Shepard, and Heather Tallis designed the GEMS project. Lydia Olander, David Yoskowitz, Chris Shepard, Heather Tallis, Katie Warnell, Sara Mason, Rachel Karasik, Kara Coffey, Christine Hale, and Kateryna Wowk contributed to planning and hosting GEMS workshops and processing workshop outcomes. Lydia Olander led writing of the paper and Katie Warnell led editing of the paper with input from David Yoskowitz, Chris Shepard, Heather Tallis, Sara Mason, Rachel Karasik, Kara Coffey, Christine Hale, and Kateryna Wowk.

Competing interests

The authors declare no competing interests.

Additional information

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