Modeling the human well-being benefits of ecosystem restoration and management for environmental decision making

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Modeling the human well-being benefits of ecosystem restoration and management for environmental decision making

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Editorial: Modeling the human well-being benefits of ecosystem restoration and management for environmental decision making

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Editorial on the Research Topic
Modeling the human well-being benefits of ecosystem restoration and management for environmental decision making

Since the release of the 2005 Millenium Ecosystem Assessment (MEA), there has been ever-growing interest and initiatives to encourage and support the use of natural infrastructure to enhance social and economic benefits to people (White House Council on Environmental Quality et al., 2022). The concept of 'ecosystem services' connects changes in ecosystems to the provisioning of goods and services that ultimately convey benefits to human well-being (Millennium Ecosystem Assessment, 2005). However, environmental management decisions are already complex and layering on human well-being benefits can seem intractable because they: require multi-disciplinary socio-ecological information; are saddled with the inherent uncertainty of natural systems; couple science-based information with subjective human values; and are embedded within a decision environment of multiple stakeholder perspectives, multi-objective tradeoffs, and limited resources (Yee et al., 2017).

This Research Topic consists of one review paper, seven original research articles, and two methods papers that present quantitative models, modeling frameworks, and tools to facilitate restoration and management of natural infrastructure to benefit human well-being through delivery of ecosystem services. The contributed papers illustrate how ecosystem services tools can be weaved throughout a generic 6-step decision process (reviewed by Sharpe et al.). These steps include:

1) clarifying the decision context, including potential impacts on stakeholders;
2) defining important objectives of the decision, including characterizing their reliance on underlying ecosystem services, and determining how those objectives will be measured;
3) developing alternative decision options to be considered, including the potential for nature-based solutions to provide ecosystem services;
4) estimating consequences of alternative options on ecosystem services objectives through models, risk analysis, or cost-benefit analysis;
5) evaluating tradeoffs and selecting an option, in consideration of preferences across different stakeholders; and
6) implementing, monitoring, and reviewing outcomes of the decision for ecosystem services and well-being.

Sharpe et al. reviews the use of the National Ecosystem Services Classification System Plus (NESCS Plus) as a unifying terminology, based on the beneficiary-focused concept of final ecosystem goods and services (FEGS), for consistency and compatibility among tools, as decision makers work through a decision-making process. The collection of compatible tools can be used to scope important stakeholders, identify and prioritize ecosystem services objectives, develop measures of ecosystem services for assessment and monitoring, and explore data, maps, and models for comparing decision options.

Hernandez et al. provides an application of FEGS to select objectives for tidal wetland restoration. A quantitative scoping analysis was used during a series of meetings with estuary program managers to identify priority stakeholders, how they benefit from restoration, and the environmental attributes most important to restore. As an alternative when direct engagement may not be practical, Jackson et al. presents a related document-analysis approach to identify ecosystem services benefits of tidal wetland restoration for different regions and organizations across the United States. Ideally, the two approaches can complement each other by providing initial insights on preliminary objectives or key groups based on analysis of existing documents before directly engaging local stakeholders.

De Jesus Crespo et al. applies a socio-ecological network approach to model and map the spatial relationships between flows of one priority ecosystem service objective, avoided sediment delivery to water reservoirs, to end users in Puerto Rico. The study estimates the supply, demand, and vulnerability of sediment retention services in reservoir drainage areas to help identify priorities for watershed-level management of reservoirs.

Singh et al. proposes quantitative methods to assess vulnerability. They propose a probabilistic framework for incorporating disaster risk into ecological risk assessment. Ecosystems and the services they provide may be vulnerable to disasters. Conversely, natural infrastructure may protect against disasters, but evaluating the efficacy of nature-based solutions for hazard risk depends on adequately estimating the likelihood and magnitude of impacts.

A more holistic multi-objective approach for linking actions to well-being benefits is applied by Fulford and Paulukonis, who use principles of network analysis to identify action pathways for achieving social, health, and economic well-being outcomes through changes in ecosystem services, alongside economic and social services. Networks help visualize relationships so that the most influential actions can be identified, and potential trade-offs examined, including selecting actions that do not contradict each other or accomplish redundant outcomes.

Kalaidjian et al. proposes methods for accounting for well-being by first assembling an evidence-base of benefits of natural infrastructure to psychological, social, and physiological human well-being. The study proposes a framework by which well-being objectives can be measured and preferences for natural infrastructure projects compared using utility functions and equity weighted cost-benefit analysis.

Lyon-Mackie et al. applies qualitative and quantitative deliberative methods for assessing the preferences of stakeholders for tradeoffs across benefits of coastal habitat restoration, and explores the degree to which preferences vary geographically. Deliberative processes have advantages over monetary valuation of ecosystem services in that they actively engage stakeholders, promote social learning, lead to shared social values, and provide insights toward implementing habitat restoration efforts that address local values.

Hesley et al. further investigates whether directly involving stakeholders in implementing restoration projects can lead to more successful outcomes, applying a logic model for program evaluation. Community scientists participating directly in coral reef restoration efforts reported behavioral changes, were more confident in communicating and advocating for coral reefs and were more likely to support conservation programs.

The involvement of a community is crucial to revitalization of brownfield sites, as well, especially for addressing community desires for the space. Mastervich et al. evaluated brownfield projects to identify design elements that resulted in ecosystem services benefits. The study also surveyed tools that may be useful for community visioning, identifying potential health and ecosystem services benefits of restoration, prioritizing sites for redevelopment by mapping vulnerabilities and assets, and designing and implementing sustainable projects.

In summary, this Research Topic leverages conceptual models and quantitative approaches to evaluate connections between environmental restoration and management actions, ecosystem condition, ecosystem services, and human health and well-being. Example applications demonstrate transferable approaches to integrate community priorities with nature-based solutions to enhance benefits of environmental remediation, ecological restoration, and community revitalization.

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Exploring stakeholders' ecosystem services perceptions across Massachusetts Bays using deliberative valuation

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Deliberative methods to assess ecosystem services values formalize community members' and stakeholders' involvement in decision-making related to natural resources management. This paper presents the methodological design and the application of a deliberative multicriteria evaluation (DMCE) method that combines the advantages of deliberation with structured decision-making to assess community-based values of four coastal ecosystem services (valued by indicators such as Total Nitrogen, Blue Carbon, Scallop Landings, Fish Abundance) and explore the spatial variability of group values along the Massachusetts coastline. We implemented four virtual deliberative workshops consisting of stakeholders from four Massachusetts Bays (MassBays) estuarine categorizations to collect quantitative and qualitative data. Quantitative data came from individual survey results and group preferences, while qualitative data were derived through the analysis of video recordings and transcripts of deliberations. Compared to previous studies, we combined quantitative and qualitative data by using applied thematic and co-occurrence analysis to identify themes of discussion during the deliberative process. Our results show that coastal stakeholders place a particular emphasis on access to clean water and services that directly support human wellbeing and provide direct economic benefits. Differences in the quantitative and qualitative results of these deliberative tasks between groups provide insight into the need for localized policymaking instead of solely regional or statewide management. Environmental managers and policymakers will utilize these insights to address local values and priorities as they work towards implementing habitat restoration efforts.

KEYWORDS

ecosystem services, applied thematic analysis, deliberative valuation, stakeholder participation, ecosystem service management

1 Introduction

Understanding nature's contribution to human wellbeing is essential for designing environmental policies, making informed and legitimate decisions, and transitioning to sustainable pathways of development. Scientists have been using the concept of ecosystem services (ESs) to communicate to stakeholders the direct and indirect benefits that people derive from the environment. The concept of ESs has become widely known since

Millennium Ecosystem Assessment (2003) which classifies ESs into four categories: provisioning (e.g., food), regulating (e.g., water purification), cultural (e.g., recreation), and supporting (e.g., biodiversity) (Millenium Ecosystem Assessment, 2003). Assessing the monetary value of ESs remains challenging due to their collective character and the limited knowledge of stakeholders concerning their complex properties (Wegner and Pascual, 2011; Farley, 2012; Parks and Gowdy, 2013).

Responding to these challenges has led to the development of valuation techniques that actively engage stakeholders in decision-making and provide a framework for building their knowledge of socio-ecological systems' complexity. In particular, deliberative forms of ES valuation have been used consistently in recent decades to ascertain said values and communicate them efficiently to improve policy advice (Guerry et al., 2015; Kenter et al., 2016; Orchard-Webb et al., 2016; Mavrommati et al., 2021).

A deliberative process creates the space for in-depth discussion and effective interaction among participants and may lead to value convergence (Murphy et al., 2017). When first introduced to the deliberative process, participants may have pre-set individual values based on personal experience, knowledge, or morals. Individual values are challenged within the deliberative process and may shift to the so-called shared social values. Previous studies have shown that social learning, improved engagement, and a higher level of interconnectedness among participants that occur within the deliberative process link individual and shared social values (Brymer et al., 2018; Eriksson et al., 2019; Mavrommati et al., 2021).

There are many deliberative valuation techniques to elicit monetary and non-monetary values (Lennox et al., 2011; Wanek et al., 2023). In this study, we used the deliberative multicriteria evaluation method (DMCE) because it 1) combines the advantages of decision theory (structure and transparency) with deliberation to elicit shared social values (collective preferences) that reflect local knowledge and experiences (Proctor and Drechsler, 2006; Kenter et al., 2016) and 2) allows to include in the assessment task ecosystem services that may have different measurement units, provide intangible benefits, and/or cannot be assigned in monetary terms (Belton and Stewart, 2002) The DMCE method provides the appropriate framework to encourage and allow citizens and stakeholders to actively contribute to decision-making, resulting in heightened community involvement and understanding, leading to better outcomes and socially justifiable choices in environmental policy formation and planning (Elliott and Kaufman, 2016). Shared social values usually differ from the aggregate values of the group's individual members (Mavrommati et., 2021; Murphy et al., 2017).

Utilizing discourse-based methods to explore people's pluralistic values regarding specific ecosystems services allows for the representation of community members from different professions and personal backgrounds who may not otherwise be involved in formal environmental decision-making (Kenter et al., 2016; Borsuk et al., 2019; Walz et al., 2019). For example, a realtor and a fisherman engaging with the same ecosystem likely utilize and value the services it provides differently; without actively soliciting their opinions and exploring the reasoning behind them through a process such as deliberative valuation, these differences of opinion (or, conversely, points of agreeance) would likely go unrepresented in policymaking.

In the absence of formal valuation exercises, simply naming the services provided by an ecosystem helps increase public recognition and knowledge and, therefore, their recognition in environmental management; deliberative valuation offers benefits beyond simple awareness by utilizing transdisciplinary methods to examine the nuances of complex, interconnected natural systems (Costanza et al., 2017). Failing to consider plural values in managing natural systems may create conflicts resulting in policy outcomes not supported by the involved stakeholders' (Walker, 2010; Hossu et al., 2018).

Even though there is a growing literature in the field of deliberative valuation, the method's outputs have not been translated into decision changes as results are often not presented in a format that is useful for policymakers (McKenzie et al., 2014; Posner et al., 2016; Handmaker et al., 2021). Designing valuation research collaboratively with the end-users of the results as well as presenting said results both quantitatively and qualitatively can help to minimize this disconnect (Wyborn et al., 2019). Quantitative data alone is often met with resistance, whether that stems from fears of manipulation or perceived disconnect from real-world situations–qualitative data, particularly that in the form of narratives, provides more useful information to stakeholders and policymakers alike (Handmaker et al., 2021). Contextualizing an issue through discussion of lived experiences yields more personal and tangible results, the preference for which is well documented by science communication literature (Dahlstrom Michael, 2014; Handmaker et al., 2021).

While deliberative processes in an environmental management context have been well studied and documented, and their impact on decision-making processes has been acknowledged, relatively few studies explore ES valuation through the lens of spatial variability (Kenter et al., 2016; Eriksson et al., 2019). Exploring the differences in ES values from the perspective of geographic usage patterns allows for more efficient resource usage and targeted management (Bennett et al., 2015). Understanding variations in how local communities value the benefits received from a given ecosystem allows for restoration or conservation efforts to be implemented first at the locations where a service is most highly valued, resulting in the efficient allocation of scarce resources. Given the multifunctional nature of ecosystems, asking stakeholders to consider the importance of multiple ESs in relation to each other furthers the goal of increased specificity in management decisions (Manning et al., 2018).

This paper aims to explore whether stakeholders' coastal ESs prioritization differs along the Massachusetts coastline by using quantitative and qualitative data. To address this overarching goal, we employed the DMCE method. We organized three workshops with stakeholders in the study area to evaluate the ESs provided by Eelgrass and Salt Marsh Habitats. This paper addresses the following questions: 1) is there spatial variability in group ESs values across Massachusetts embayments? 2) do deliberative valuation methods offer participants a space for value convergence? 3) in what ways are group ESs values similar or different? Compared to other studies, we used a mixed methods approach to evaluate the role of spatial variability in ES valuation by utilizing pre-established categories of Mass Bays embayments and analyzing the workshop outputs quantitatively and qualitatively.

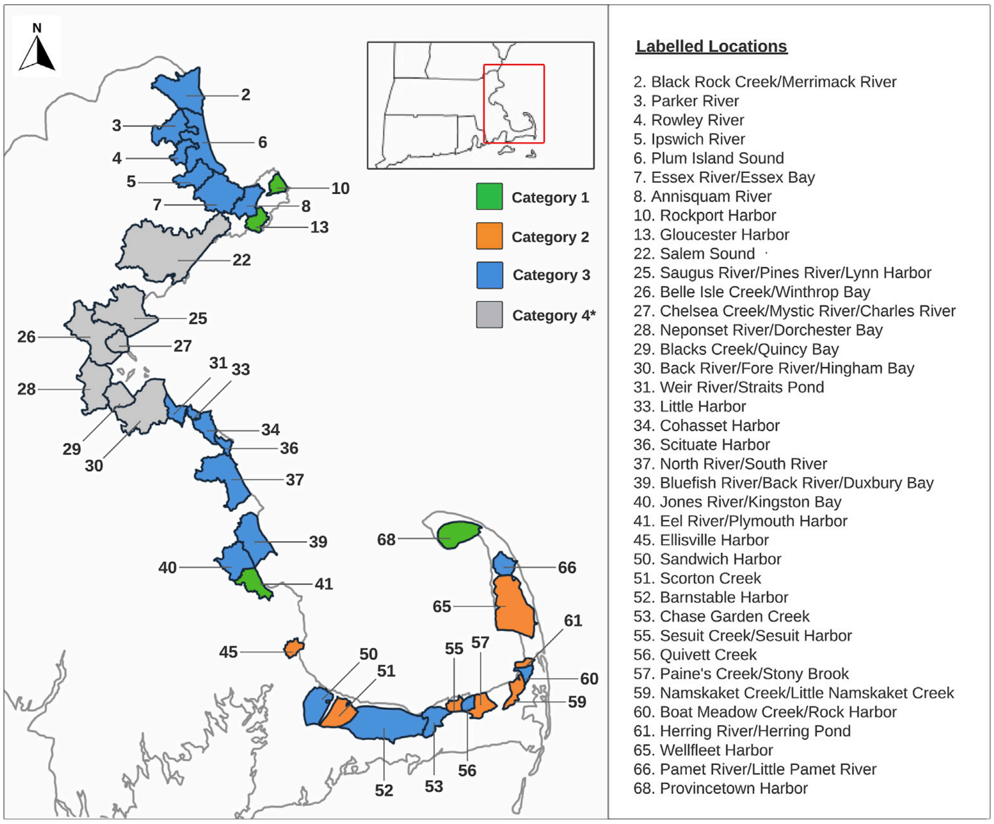

FIGURE 1
MassBays embayment categories map. All labeled and categorized locations are embayments. *Category 4, shown in grey, was not included in the final analyses.

2 Methods

2.1 Study location

We applied the DMCE method to estuarine assessment areas defined by MassBays in the Estuary Delineation and Assessment 2.0. In addition to delineating Massachusetts coastal estuarine watershed boundaries, this report also identified unique geospatial attributes and classified human usage patterns of said estuaries (Geosyntec, 2017). The MassBays planning area (extending from Salisbury at the New Hampshire border to Provincetown) was spatially delineated using ecosystem-based landward and seaward boundaries. The area was then subdivided into 65 assessment areas, including 44 embayments, based on sub-watersheds. Estuarine habitats in the 44 embayment areas include tidal flats, eelgrass beds, salt marshes, and other estuarine resources. These habitats provide a plethora of ecosystem benefits to both human and natural systems; flora and fauna are provided with the necessities for different stages in their life cycle, while humans experience direct benefits such as access to recreation and economic resources as well as indirect benefits such as pollution filtration and protection from storm surges (Granek et al., 2010).

After delineation, each assessment area was characterized using spatial distribution of resource and stressor attributes. Details of the delineation methodology as well as analyses of datasets are provided in the Estuary Delineation and Assessment Report (Geosyntec, 2017). Coastal Massachusetts has a rich and complex geomorphology, resulting in estuarine and non-estuarine embayments with distinct natural characteristics and anthropogenic conditions. For management purposes, the embayments were classified into four categories based on a subset of resource and stressor attributes (see Supplementary Table S1). Principal component analyses (PCA) and partitioning around medoids (PAM) was used to cluster embayments with similar resource and stressor attribute levels (Nagpal et al., 2013; Jolliffe and Cadima, 2016). The PCA and PAM analyses identified four clusters of embayments labeled categories 1 through 4, as shown in Figure 1 (Hanley, 2021).

2.2 The swing weighting method

To elicit ES values from participants within the context of DMCE methodology, we employed the "swing" weighting method that is easy for the participants to understand and perform (Keeney and Raiffa, 1993). This method starts from a hypothetical reference alternative where all attributes are set to their worst potential value. Based on this hypothetical reference alternative, other hypothetical alternatives are developed in which one attribute at the time is "swung" to its best possible level. The deliberative processes for each ecosystem within these workshops

TABLE 1 Stakeholder groups and their perceived value to group deliberations.

Title	Position description	Perceived significance of inclusion
Chamber of Commerce Member	A voluntary member of a town or city's chamber of commerce, which is defined as a body of businesses and professionals working together to build a healthy economy and improve a community's quality of life	Chamber of Commerce members generally have knowledge regarding the economic dynamics of their community through communication with local businesses and enterprises
Conservation Agent	Performs technical inspection work including field visits, inspections of site work, drafting of Orders of Conditions, attending Commission meetings. Ensures compliance with applicable federal, state, and regulations and bylaws	Thorough understanding of applicable regulations and current condition of local wetlands. Probable previous understanding of ESs specifically in an estuarine context
Conservation Organization Member	A member of a nonprofit chartered institution, corporation, foundation, or association founded for the purpose of promoting environmental conservation	These organizations self-identify their commitment to the protection of a community's natural resources and often have direct communication with the public
Conservation Planner or Administrator	Assesses possible environmental repercussions of development on a given area of land in order to permit or deny proposed projects	A conservation planner/administrator's ability and skill set to determine whether the land is worthy of special consideration is an important skill set in policymaking
Indigenous Leader	Members of indigenous groups in each local area who engage in educational activities promoting knowledge about indigenous culture, history, traditions, and more	Indigenous leaders bring their knowledge and understanding of cultural values and ESs to discussions and advocate for the continued health of their communities
Shellfish Constable	Responsible for the protection of a town's shellfish through the enforcement of established environmental laws and regulations	Has knowledge of the state's local and environmental laws as well as the conditions of the local environments that support shellfish
Researcher/Specialist	Individuals operating within the professional sphere or academia who conduct research or have extensive knowledge and education regarding a given topic. In this case, those recruited had a focus in one or more scientific disciplines within the natural or social sciences	A researcher or specialist generally has extensive knowledge on their subject of study along with years of relevant experience
Tourism Board Member	A voluntary member of a town or city's tourism board, which is defined as a group responsible for marketing their town's tourist attractions and businesses to attract visitors for the benefit of the town and industry	Have a comprehensive understanding of services and aesthetics that promote tourism
Yacht Club/Marina Official	A marina is a structure containing docking facilities located on a navigable waterway. Some marina official positions could include office administration positions as well as maritime office positions	Marina officials have knowledge of regulations that regulate boat sewage, pollution, health and fire regulations, etc. They also have contact with residents who use these ecosystems for recreation or conducting business

utilized a set of several hypothetical alternatives formulated using multiattribute value theory (MAVT), which yields weights in an additive multiattribute utility function (Keeney and Raiffa, 1993; Eisenführ et al., 2010; Mavrommati et al., 2021). This method requires only the knowledge of the potential range of values an attribute might take and creates an opportunity for participants to discuss and score the given attributes (Mavrommati et al., 2017).

Tradeoff weights represent the relative importance of the attributes inferred from the participant ratings using the swing weighting method. They show the willingness of groups to compromise on one objective in favor of improvement in another objective. The weights were calculated using the following equation:

$$w_i = \frac{s_i}{\sum_i^n s_i}$$

where w_i are the trade-off weights for each attribute, and s_i is defined as a contingent rating for the ith choice bundle (Neumann and Morgenstern, 2007).

2.3 Participant recruitment

In our initial pool of potential workshop participants, we identified and included a diverse range of stakeholders based on two criteria: 1) stakeholders' specific knowledge relevant to the habitats and ESs selected for this study (see Section 2.4 for a detailed description) and 2) stakeholders' established connection (e.g., livelihood, their position on a council or other local management body, or through their membership in a local indigenous community) to the embayment evaluated. Contacts were identified through internet searches for various titles and a city, town, or location in each category (i.e., "Barnstable Harbormaster"). When reaching out to a body such as a town council or a nonprofit organization, an invitation was extended to nominate a suitable representative. We also used the snowball sampling method, a type of sample recruitment strategy whereby all or a portion of participants who are asked to engage with a study are not directly recruited by the researcher but through other persons who may connect them as potential participants (Reed, 2008; Marcus et al., 2016; Naderifar et al., 2017).

A researcher not familiar with established networks of environmental science professionals conducted outreach procedures to reduce selection bias. In some cases, participants were contacted based on previous relationships with researchers–specifically the recruitment of indigenous peoples. We approached approximately 120 potential participants to participate in one of the four workshops, and 28 agreed to participate. Recruited participants were assigned workshop groups based on their location; all participants in a given workshop were stakeholders residing in the same specific

TABLE 2 Sources and assumptions made for each ecosystem attribute.

Benefit	Attribute	Data source	Assumptions
Biodiversity	Fish Abundance	Carlisle et al. (2005)	A larger area of habitat indicates a larger population of fish
			Eelgrass: 1 acre supports up to 40,000 fish
			Salt marsh: 1 acre supports 688 fish
Food	Shellfish landings	SAFIS Standard Atlantic Fisheries Information System	A larger area of habitat indicates a larger population of bivalves
Climate Regulation	Blue Carbon	Ouyang and Lee (2014)	Salt marsh and eelgrass remove a measurable amount of carbon from the atmosphere equivalent per acre of habitat. This amount was translated in units of cars' or homes' carbon output removed from the atmosphere per year to provide relatable context
			Eelgrass: 1 car/yr/13 acre; 1 home/yr/30 acre
			Saltmarsh: 1 car/yr/10 acre; 1 home/yr/22 acre
Water quality	Total nitrogen	NOAA (2016)	Salt marsh and eelgrass both take up nitrogen from their environment, which contributes to overall water quality
			Eelgrass: 1 acre removes 6.5 lbs TN/yr
			Saltmarsh: 1 acre removes 500 TN/yr

category (for example, participants in the first workshop were all residents of towns within the geographic boundaries of category 1). Table 1 details the groups of stakeholders we aimed to recruit and their perceived potential contribution to the deliberative process. Ideally, the DMCE method requires participants to be identified early in the process with the goal of including them in the study design and attribute selection process; this was not possible due to both the collaborative nature of this work and a lack of resources. While we recruited participants for four workshops as dictated by the four identified embayment categories, we were unsuccessful in recruiting the minimum number of participants to conduct a workshop for category 3.

2.4 Attribute selection and hypothetical management options

This study focused on two habitats, eelgrass beds, and salt marshes, due to their ecological and socioeconomic significance and the availability of reliable data across all embayments. A diverse group of scientists, e.g., biologists, geologists, ecologists, and ornithologists, was convened for each habitat, and over a series of four meetings discussed ESs provided by the two habitats and how they could be represented in a way that would be easily understandable by workshop participants. The output of these discussions was the identification of four attributes, outlined in Table 2, which were selected based on the applicability to both habitats and the availability of good and reliable data.

The best- and worst-case values for each attribute correspond to a range of hypothetical alternative management choices and depend on the cluster of embayments being considered, given that each cluster has its own unique set of stressors and capacity that dictate what management actions are applied to get the best results. Such hypothetical management alternatives included but were not limited to upgrading wastewater treatment facilities, increasing dredging activity to improve navigation channels, and building hardened shorelines to protect against flooding; each identified management alternative had direct, measurable effects on the chosen ecosystem attributes and could be translated into a range of projected future values that formed the basis of the deliberative tasks using the swing method. Similar management alternatives were used to develop each category's deliberative tasks, but slight variations to reflect the anthropogenic stressors unique to each group of embayments were introduced. Table 3 details the projected values for each attribute within the context of the specific conditions of a given category.

The choice between the alternatives described will depend on several factors, including costs and resource capacity. For example, upgrading an existing wastewater treatment plant (WWTP) and growing shellfish to reduce TN may be less expensive than building a new WWTP. However, using biological methods to reduce nutrients also means that a lot of space must be available, which may not be the case in some embayments.

2.5 Workshop structure

Before the workshop, stakeholders received further information about the workshop logistics and an informational video presentation (see Supplementary Video). This presentation provided information about the location and characteristics of their category, the two habitats that would be discussed, and the four ESs provided by each that would form the basis of the deliberative process.

While many participants were familiar with the ecosystem services in question, we decided to provide all participants with the same basis of knowledge and understanding to hopefully reduce confusion or a lack of understanding during the deliberative process. Particularly important was ensuring a collective understanding of the definition of an ES as this concept formed the basis of all tasks as

TABLE 3 Definitions of attributes. Metrics were estimated using both historic and current data to project current, best possible, and worst possible values based on a set of hypothetical future choices.

ES	Attribute and units	Definition	Habitat	Category	Current value	Best value	Worst value
Biodiversity	Fish Abundance (millions of fish)	The number of individual fish present within a defined area	Salt marsh	1	0.3	0.6	0.1
				2	1.5	3.4	0.5
				3	17.9	23.8	8
			Eelgrass	1	51.5	56.6	51.5
				2	44.2	200	26.52
				3	57.2	104.7	44.2
Availability of Food	Shellfish Landings (thousands of pounds per year)	The number of individual fish present within a defined area	Salt marsh	1	492,000	329,000	164,500
				2	8.7	16.5	1
				3	3,300	4,000	250
			Eelgrass	1	492,000	329,000	2,000
				2	8.7	16.5	2
				3	3,300	4,000	500
Carbon Sequestration	Blue Carbon (metric tons per year)	The number of individual fish present within a defined area	Salt marsh	1	206.1	431.5	63.6
				2	1,025	2,029	512.5
				3	12,1281.2	16,318.1	5,453.9
			Eelgrass	1	432.6	475.8	432.6
				2	371	1,695	222.8
				3	480.9	879.7	371.5
Water Quality	Total Nitrogen (pounds per year)	The number of individual fish present within a defined area	Salt marsh	1	218,718	458,115	67,548
				2	1,080,000	2,154,000	344,000
				3	13,037,411	17,322,835	578,693
			Eelgrass	1	8,240	9,064	8,137
				2	7,075.3	32,294	4,376
				3	9,159	16,756	7,075

well as the presentation of the attributes that we used to represent them (Murphy et al., 2017).

Each workshop was conducted over 3 hours on the virtual meeting platform Zoom. We began by introducing the participants to each other and the researchers, moderator, and experts present. A concise version of the video presentation participants viewed before their workshop was presented to refresh their knowledge of the concepts and ESs in question. The assessment tasks followed, starting with the eelgrass ecosystem and ending with the salt marsh ecosystem, with a break in between.

Besides the stakeholders present at each workshop were a moderator, two technical experts, two researchers, and an impartial expert. The role of the moderator was to encourage respectful and productive deliberative discussions as well as keep the group focused on their goal of representing their local communities and promoting the common good (Schaafsma et al., 2018). The moderator refrained from asking any leading questions or inserting her own opinions, instead simply reminding participants of the task at hand when necessary and ensuring our pre-determined timeline was upheld. Our two technical experts were ecologists familiar with the ecosystem dynamics in question. Their role was to answer participant questions during the workshop so deliberation could continue with greater collective understanding. The two researchers were present at all workshops to observe proceedings and assist in virtually conducting the assessment tasks. Lastly, the impartial expert who was the lead researcher of this project assisted in the workshop by correcting misleading information and clarifying any technical questions related to the individual and group assessment tasks. During the tasks, a student researcher used a shared dynamic virtual interface that visualized changes in preferences in real-time during group discussions (Tobin et al., 2020). In addition, we tested our method by running a pretest workshop with MassBays' regional staff (who regularly work with the stakeholder groups) to ensure that the flow of the workshop is

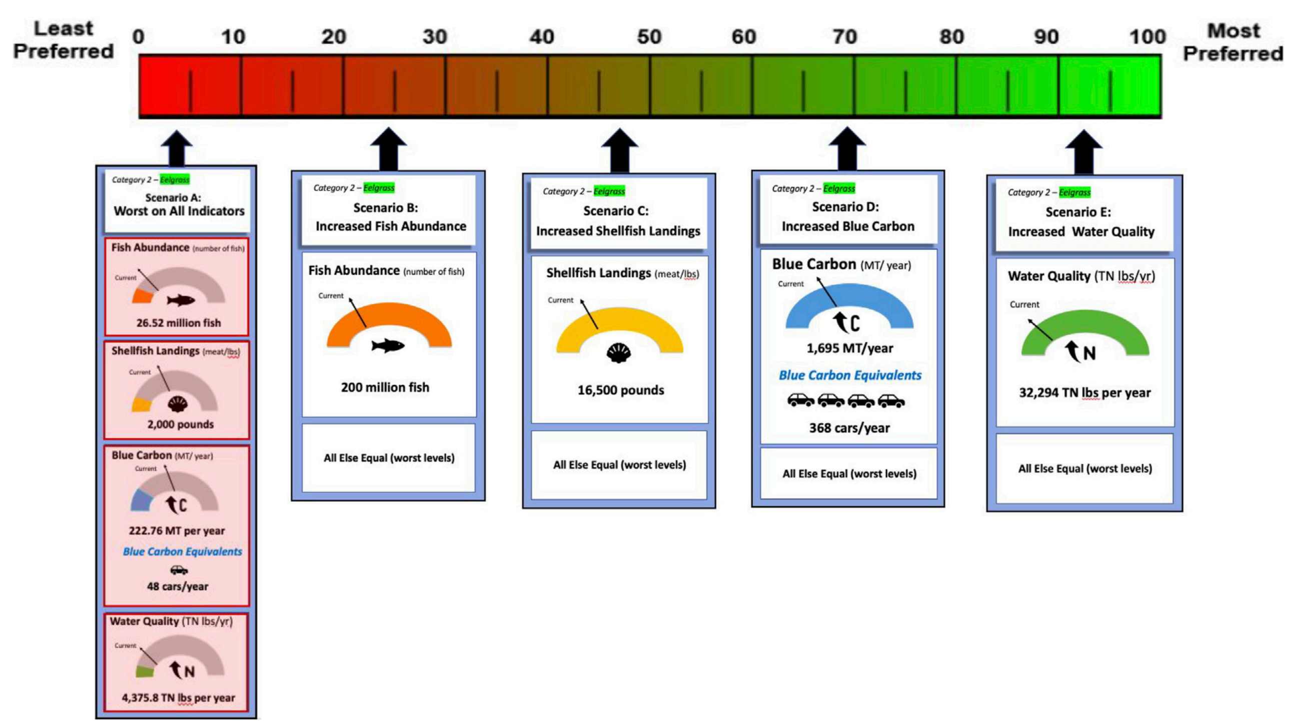

FIGURE 2
Decision option cards used for group assessment tasks. This set of cards was formulated for Group 2's eelgrass habitat assessment task; each group was presented with two unique sets of cards, one set each for the salt marsh and eelgrass habitats, based on data collected by various sources found in Table 2.

smooth, the information conveying ESs was clear and that the workshop assessment tasks described in Section 2.4 could be performed in a virtual environment.

At the start of the workshop, participants were directed to complete a pre-deliberation survey based on their individual valuation of the ESs. Similar to Murphy et al. (2017), the survey was administered in the form of a questionnaire that asked each participant to numerically rank the relative importance of ESs within the context of each ecosystem. This choice was made based on the recommendations of the pretest workshop participants and the relevant literature (Burk and Nehring, 2022). In particular, we elicited complete swing weights in the individual tasks during the pretest workshop, and participants advised us to use rank order instead because it is an easier and less time-consuming elicitation method. After engaging in the deliberative process, an identical post-deliberation survey was administered to track changes in individual values engendered by group discussions.

2.6 Deliberative task design

We developed the deliberative task using the swing weighting method (Section 2.2). In particular, we presented five decision alternatives for each ecosystem to the workshop participants based on the best and worst values of the attributes. The best and worst values of each attribute correspond to two states of the world that pair a broad range of hypothetical management future choices (Table 2). The overall social value of the ecosystem services provided for various hypothetical management future choices hinges upon the projected attribute levels and the weights assigned by the stakeholders. We used the term 'decision options' to communicate the alternatives to participants. Each workshop group was asked to place the five decision options along a meter stick with a scale of 0–100, with 0 being the least preferred decision option and 100 being the most preferred as shown in Figure 2. The reference alternative with all attributes at their worst level was always set to 0. Groups could decide to rank two decision options at the same numerical value if they felt they were equally preferred.

Deliberations began with each stakeholder voicing their initial rankings of the decision options at the moderator's request. Once all stakeholders had voiced their opinions, a moderated debate ensued, during which time participants attempted to come to a consensus regarding how they would rank the four decision options. Participants were encouraged to consider alternative viewpoints, ask questions if they did not understand a particular concept or perspective, and consider how their group rankings reflected their overarching goal of promoting the common good. Once deliberation concluded, the moderator requested that the group categorize their final rankings as a consensus decision or a compromise. While the goal of the exercise was to reach a consensus, this result was not forced on participants - they were encouraged to express any degree of compromise they accepted to finish deliberations. Individual participant convergence toward final group ranking decisions was

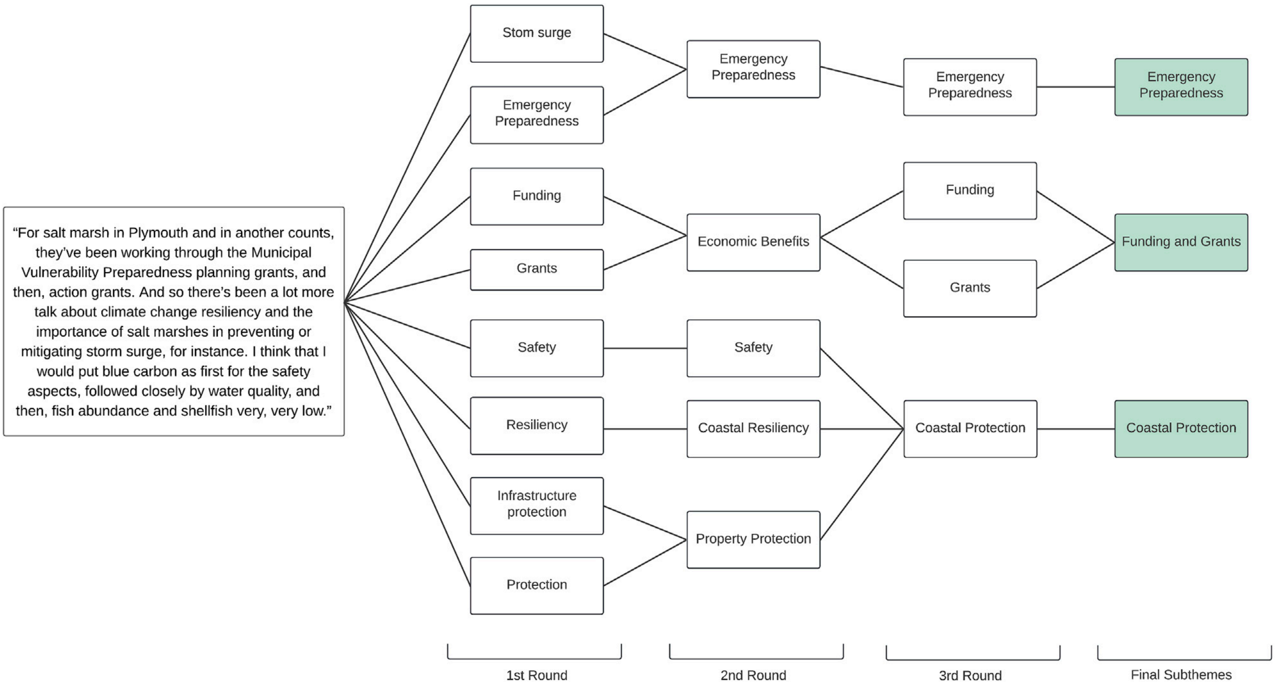

FIGURE 3
Visual representation of the codebook formulation process. The 1st Round column gives the initial keywords attributed to the quote by coders, the 2nd and 3rd Round illustrate the refinement process that occurred with consideration for all other quotes in a group's transcript, and the final subthemes listed were those included in the final codebook. As shown by the pathway terminating in the "Funding and Grants" subtheme, the refinement process could include both combining terms as well as distinguishing between them based on the desired level of specificity. This quote was taken from Group 2's salt marsh assessment task.

also explored through the calculation of Kendall's τ rank coefficients, which were derived using results from the individual pre-deliberation surveys and final group rankings (Kendall, 1938).

2.7 Applied thematic analysis

Video and audio recordings of each category's Zoom meeting were used to build a thematic framework through which each category was analyzed. Audio recordings were transcribed by an outside firm and checked for accuracy by multiple members of the research team. These transcripts were used to perform an applied thematic analysis, which allows for qualitative data to be analyzed in a systematic manner (Mackieson et al., 2018; Guest, 2012). Thematic analysis is a broad term with many applications; in this case, it was used to identify common themes and subthemes discussed by participants during deliberations that influenced how their individual rankings of each ES morphed over time.

Three members of the research team, referred to as "coders," analyzed each category's transcript to identify these common themes. This process began with creating an Excel spreadsheet containing each quote, its corresponding timestamp, and several columns of codewords associated with each quote. Not all quotes from the deliberation were included in the analysis process–only those expressing a clear opinion regarding the value of a service or the reasoning behind a ranking decision were included to avoid clutter and double counting. Coders met regularly to discuss and refine the index of codewords through multiple iterations of quote analysis; Figure 3 portrays an example of how codewords were grouped together over time to identify subthemes. In each iteration, of which there were approximately 6 for each category, a different coder would initially review and identify codewords. Subsequently, the other two coders would examine and refine their work. By assigning equal tasks to three coders, we hoped to minimize individual influence and maintain consistency (Mavrommati et al., 2021).

2.8 Co-occurrence analysis

Co-occurrence analyses use qualitative data to explore the rate at which certain keywords are brought up by individuals in tandem with the goal of illustrating how ideas are clustered together visually (Scharp, 2021). Keywords (or in this case, subthemes) are not necessarily an adequate proxy to represent highly nuanced discussions such as those held by each group in this study, but they do serve to identify general thematic relationships and trends (Guest, 2012).In order to determine co-occurrence frequencies of subthemes, all possible pairings of the final subthemes assigned to a given quote were numerically represented with a value of one. To give an example, if the subthemes "commercial enterprises," "nutrient levels," and "public engagement" were assigned to the same quote, a total of three co-occurrences would be tabulated: 1) commercial enterprises with nutrient levels 2) commercial enterprises with public engagement and 3) nutrient levels and public engagement. Once all quotes are analyzed, the final co-occurrence frequencies represent all the instances in which two given subthemes were assigned to the same quote.

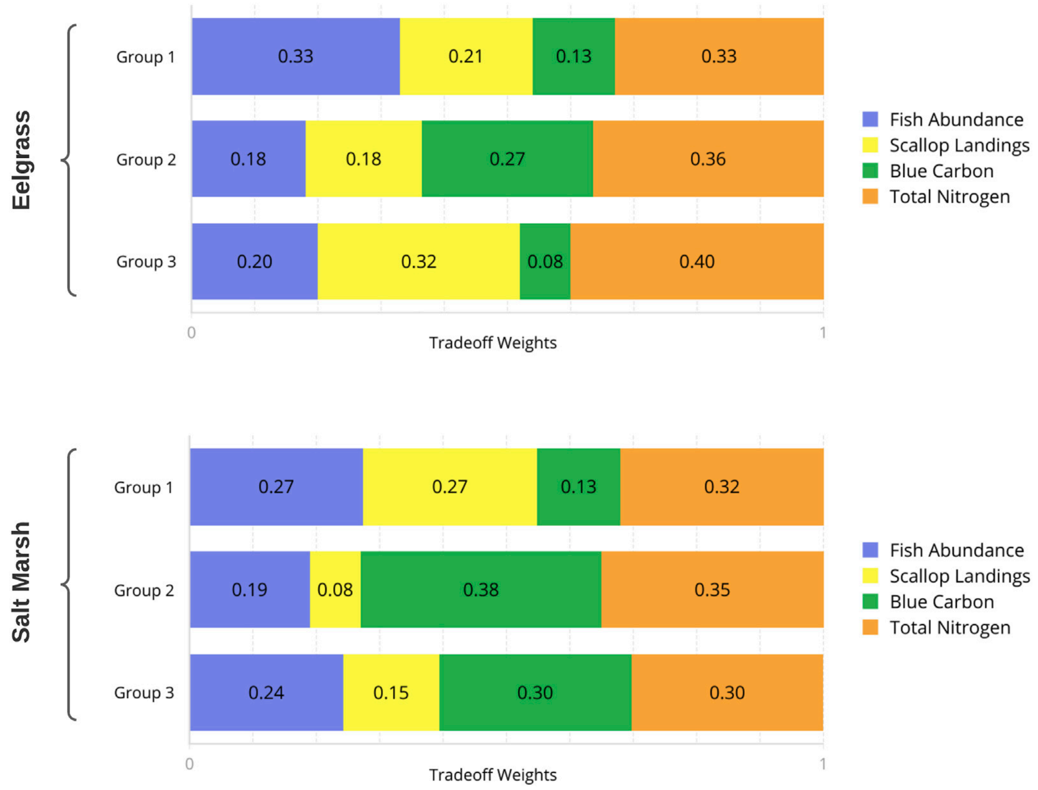

FIGURE 4
Tradeoff weight results by ecosystem and workshop group.

3 Results

3.1 Quantitative results

The pre- and post-deliberative surveys were used alongside group assessment task results to perform quantitative analyses with the purpose of identifying the ES preferences of each group.

3.1.1 Results by category

Final rankings of each attribute varied across both habitats and workshop groups. The sole commonality was the elevated level of importance universally placed on the Total Nitrogen attribute–apart from a second-place ranking given by Group 2 with respect to the salt marsh ecosystem, Total Nitrogen received the highest ranking in every assessment task. When considering attribute rankings respective to each ecosystem, groups emphasized the importance of the Blue Carbon attribute during the salt marsh assessment tasks and discussed the Fish Abundance and Shellfish Landings attributes more frequently during the eelgrass assessment tasks, although this did not necessarily translate to higher relative rankings.

The quantitative outcomes of the deliberative assessment tasks were first portrayed as tradeoff weights and shown as an initial result to participants at the conclusion of their deliberation. As shown in Figure 4, participants were least willing to accept compromises regarding the Total Nitrogen attribute in the context of both habitats. Shellfish Landings and Fish Abundance tradeoff weights show variability across habitats, but Blue Carbon was given a generally higher weight in the context of the salt marsh ecosystem.

Figure 5 gives the quantitative results of the salt marsh participant surveys and assessment tasks: 1) Total Nitrogen consistently ranked highly both before and after deliberations 2) Blue Carbon was ranked highly by Groups 2 and 3, whose corresponding categories have significantly more salt marsh area than Group 1 3) Fish Abundance and Shellfish Landings were generally given lower rankings with Blue Carbon and Total Nitrogen except for Group 1, which may again be due to the relatively small area of salt marsh under consideration for this category.

Figure 6 gives the accompanying quantitative results to Figure 5 for the eelgrass ecosystem: 1) Total Nitrogen was unanimously ranked as the most important service to this group at all stages apart from a single participant in the pre-deliberation survey 2) Fish Abundance was perceived to be the least important attribute by all except for participants 3 and 6 and 3) Blue Carbon was almost unanimously ranked as the second most important attribute.

3.1.2 Standard deviations of rankings

Table 4 shows standard deviation values between participant rankings in the pre-and post-deliberation surveys for each attribute in each group. The final column gives the change in value of a group's standard deviation—a negative change value indicates a lower standard deviation in the post-deliberation survey, which implies that participants' opinions converged regarding the

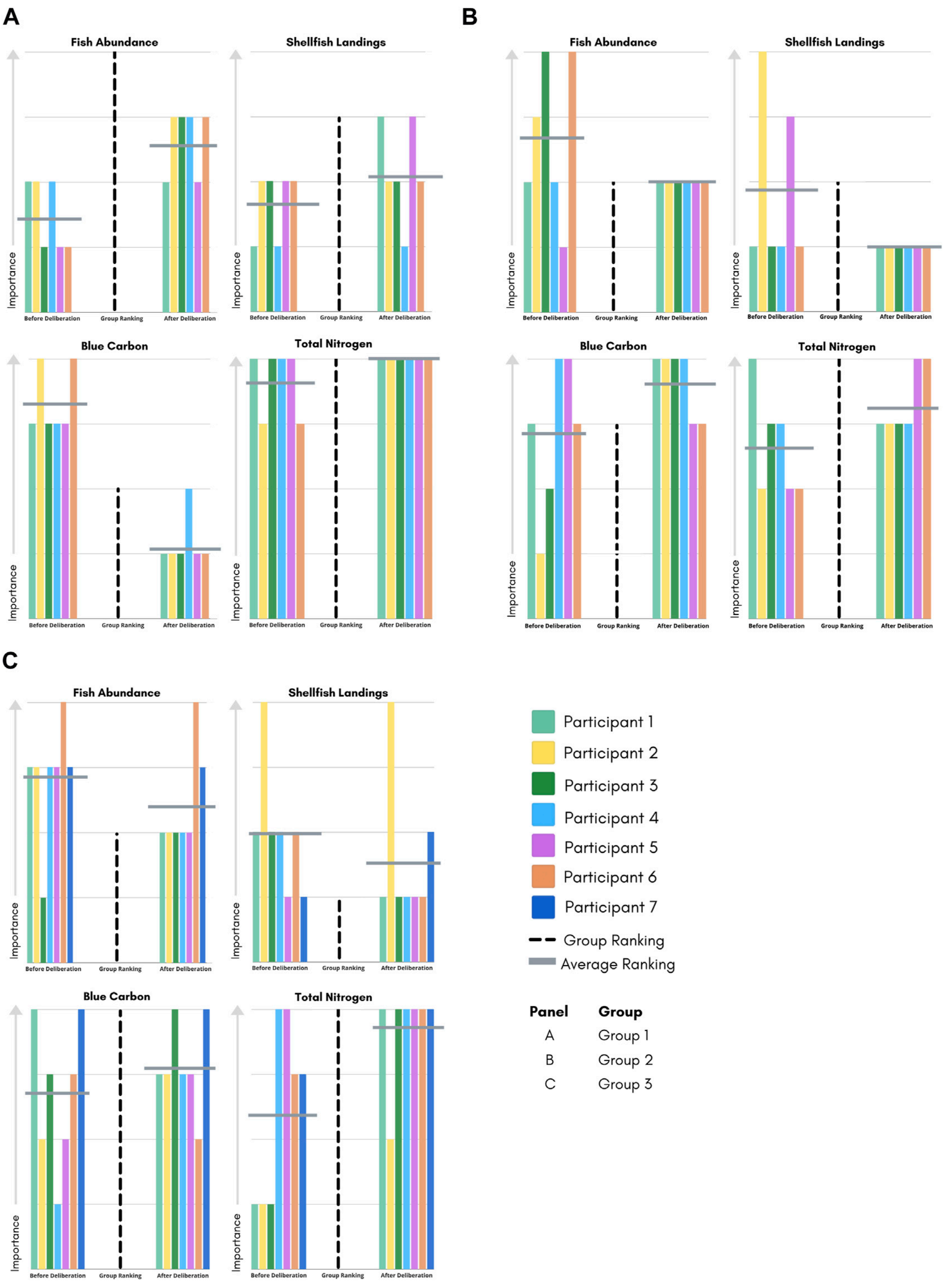

FIGURE 5
Salt marsh rankings bar plot. Individual rankings before and after deliberation are compared with group rankings at the close of the assessment task. Each panel is divided into four sub-panels displaying the rankings of the four ES attributes. The *y*-axis represents the level of importance assigned to a given attribute. The *x*-axis displays three stages of the workshop. Individual rankings given in the pre- and post-deliberation surveys (labelled here as "Before Deliberation" and "After Deliberation" respectively) are represented by colored bars assigned to a particular participant, group rankings are represented by a dotted black line, and the average rankings across individuals for each survey are represented by a grey bar (see legend). Panels **(A)** and **(B)**, which represent Groups 1 and 2, had 6 participants as opposed to Group 3's 7 and therefore do not display the terminal dark blue bar shown in panel **(C)**.

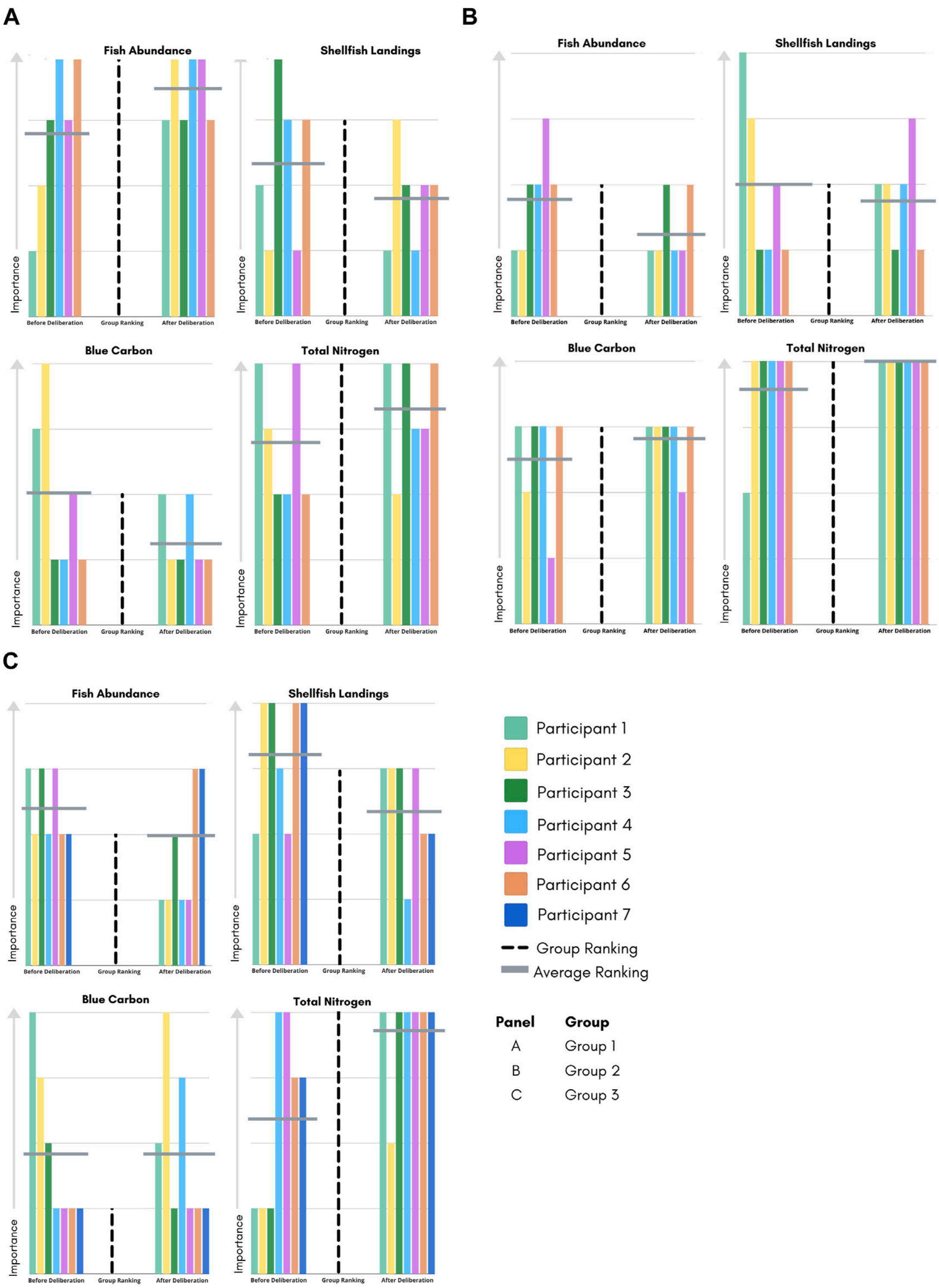

FIGURE 6
Eelgrass rankings bar plot. Individual rankings before and after deliberation are compared with group rankings at the close of the assessment task. Each panel is divided into four sub-panels displaying the rankings of the four ESs attributes. The *y*-axis represents the level of importance assigned to a given attribute. The *x*-axis displays three stages of the workshop. Individual rankings given in the pre- and post-deliberation surveys (labelled here as “Before Deliberation” and “After Deliberation” respectively) are represented by colored bars assigned to a particular participant, group rankings are represented by a dotted black line, and the average rankings across individuals for each survey are represented by a grey bar (see legend). Panels **(A)** and **(B)**, which represent Groups 1 and 2, had 6 participants as opposed to Group 3's 7 and therefore do not display the terminal dark blue bar shown in panel **(C)**.

TABLE 4 Standard deviation of pre-and post-deliberation survey results grouped by ecosystem and attribute. Standard deviations represent the extent of deviation from the mean ranking for an attribute in a specific group.

Ecosystem	Attribute	Group	Pre-deliberation	Post-deliberation	Change in value
Eelgrass	Fish Abundance	1	1.17	0.55	−0.62
		2	0.75	0.55	−0.24
		3	0.53	0.82	0.28
	Shellfish Landings	1	1.21	0.75	−0.46
		2	1.26	0.75	−0.51
		3	0.95	0.79	−0.16
	Blue Carbon	1	1.26	0.52	−0.75
		2	0.84	0.41	−0.43
		3	1.21	1.21	0
	Total Nitrogen	1	0.98	0.82	−0.17
		2	0.82	0	−0.82
		3	1.4	0.76	−0.64
Salt Marsh	Fish Abundance	1	0.55	0.52	−0.03
		2	1.21	0	−1.21
		3	0.9	0.79	−0.11
	Shellfish Landings	1	0.52	0.75	0.24
		2	1.33	0	−1.33
		3	1	1.13	0.13
	Blue Carbon	1	0.52	0.41	−0.11
		2	1.17	0.52	−0.65
		3	1.11	0.69	−0.42
	Total Nitrogen	1	0.52	0	−0.52
		2	0.82	0.52	−0.3
		3	1.51	1.35	−0.17

importance of a given attribute. A positive change value indicates that individual responses became more disparate after the assessment task.

Regarding the eelgrass ecosystem, all categories exhibited increased agreement in attribute rankings across all attributes–the only positive standard deviation change recorded was the Fish Abundance attribute in Group 3. Regarding the salt marsh ecosystem, Fish Abundance, Blue Carbon, and Total Nitrogen saw a negative change in standard deviation across all groups. Shellfish Landings saw an increase in standard deviation in both Group 1 and Group 3. All standard deviation changes for Group 2 in both habitats were negative.

3.1.3 Individual participant influence on group rankings

Each participant's total time spoken was plotted against Kendall's τ rank coefficients, which signified the individual's degree of convergence with group results. No clear relationship was observed–in actuality, participants that volumetrically contributed the most to deliberative discussions showed a higher degree of variance from the group results. Those who spent less time contributing and, consequently, more time listening to the opinions of other stakeholders had higher levels of convergence with final group rankings.

3.2 Qualitative results

After completing the coding process, we found six major themes and 26 subthemes that were present in all three groups. The six themes represent groupings of subthemes related to the same topic or sphere. For example, the theme "Conservation" has six subthemes: coastal protection, environmental policy, habitat condition, habitat extent, and wildlife considerations. Subtheme definitions were formulated by the research team specifically for use within the context of this study and may not be universally applicable. A complete list of themes, subthemes, and subtheme definitions is included in Table 5. Example quotes from participants

TABLE 5 Final theme and subtheme codebook. Themes and subthemes listed in this codebook were generated using participant quotes from all three categories and thus apply to all workshop analyses.

Theme	Subthemes	Definition
Human Wellbeing	Food source	Has nutritional importance to a local community
	Recreation and aesthetics	The degree to which a habitat can provide recreational opportunities or spiritual fulfillment
	Cultural fulfillment	Satisfaction obtained from specific activities or services specific to that area which affect the way people live
	Emergency Preparedness	In the context of the coastal protection of human lives provided by habitat barriers against inclement weather
	Human Health	The potential effects an attribute could have on the health of a human body (this includes injury as well as illness)
Scale of Impact	Geographic scale	Consideration of the attribute occurred within the context of a comparison such as local vs. global or local vs. category-wide
	Immediacy of Impact	Invokes a time scale of when a certain action or trend will have a noticeable effect on the local community
	Local species significance	How a certain species affects the ranking of an attribute in a cultural, economic, or public engagement perspective
Conservation	Habitat extent	The area of a given habitat in a specified location
	Wildlife considerations	The effect of a given attribute on the health of local wildlife
	Environmental policy	Any legislation, restrictions, or protections enforced in a habitat
	Habitat condition	The overall ecological health of a habitat (excludes extent)
	Coastal protection	Protection of natural resources and/or infrastructure and inland ecosystems by a habitat
Habitat Dynamics	Wastewater treatment	The treatment of sewage before it enters aquatic environments
	Tidal flushing	The natural movement of water in and out of an embayment during tidal cycles
	Nutrient levels	The levels of various nutrients such as nitrogen or phosphorous in the water column of a habitat
	Trophic cascade	The effect an attribute or changes to an attribute might have on a given trophic level as it relates to potential systemic changes in a habitat
	Substitutability of service	The perceived ability to derive the benefits of an ES through a means other than the attribute, specific species, or other sub-topic being discussed
Economic Issues	Tourism	The economic benefits garnered through tourists coming to the area
	Profit feasibility	The amount of effort required to turn a profit when considering a specific commodity regardless of the scale of enterprise
	Commercial enterprises	Includes any businesses that profit from the services provided by a habitat such as aquaculture or fish farming
	Funding and grants	Monetary support for various environmental initiatives from private, state, or federal entities
	Employment security	The ability of a habitat to sustain a service that provides employment opportunities to members of a local community
Representation of Community Values	Public engagement	The level of attention or action a community displays regarding a given issue
	Public support	The support or lack of support a local community shows toward a given issue based on collective opinion or emotional investment
	Public knowledge	The real or perceived collective knowledge a local community has regarding a habitat, or the ESs, it provides

during the deliberative tasks can be found in Supplementary Table S2.

3.2.1 Thematic frequencies by category

Following the identification of thematic groupings, the frequencies of theme and subtheme occurrences within the assessment tasks of a given group were tabulated. Figure 7 shows the number of times each subtheme was assigned to a quote over the course of deliberation. Both assessment tasks for each group were included in the final tabulations; results are not separated by ecosystem.

Subtheme frequencies were highly disparate across the three categories analyzed. Certain subthemes, such as commercial enterprises and public engagement, had high frequencies across two of the groups but low frequency in the third. In some cases, a subtheme that was discussed frequently by one group was completely absent in the discussions of another group (for example, the "public support" subtheme was assigned to

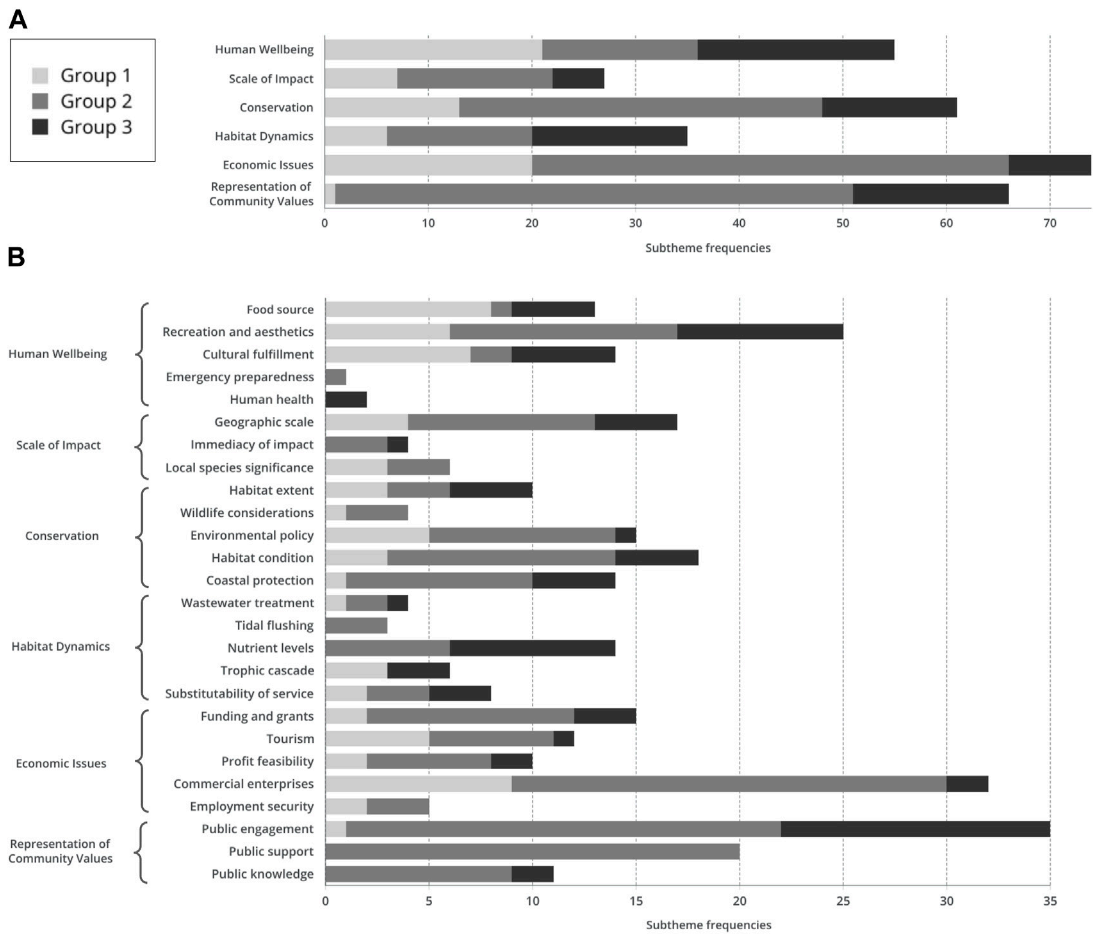

FIGURE 7
Stacked bar plot showing subtheme frequencies across both habitats by category. Results are shown organized by theme (panel **(A)**) and by both theme and individual subthemes (panel **(B)**). Bar shades represent the frequencies of a given group (see legend). The *y*-axis of panel A lists the six major themes and the *y*-axis of panel **(B)** lists the six major themes as well as all subthemes. The *x*-axis gives subtheme frequencies, defined as the number of times a given subtheme was assigned to a participant quote over the course of a workshop regardless of ecosystem.

20 quotes from Group 2 but none from Group 1). The results organized by overall thematic grouping further emphasize the variety of results recorded; as seen in panel A of Figure 7, the most discussed thematic group in one category could be the least discussed in another. Also notable is the difference in scale when interpreting subtheme results–the final quote lists of Groups 1 and 3 contained far fewer useable quotes than Group 2 due to differences in group dynamics.

3.2.2 Co-occurrence analysis

To visualize co-occurrence frequencies, matrices were constructed for each category that contained all subthemes as both the rows and columns; intersecting cells describe the number of times a subtheme combination was observed in a group's discussion (McLellan-Lemal et al., 2003). To produce the heat map shown in Figure 8, subtheme co-occurrences were grouped into their larger thematic categories. A cell value of zero conveys that no subtheme co-occurrences were recorded within the two intersecting thematic groups at any point in a group's discussion. For example, Group 2's heat map shows that the highest co-occurrence frequencies between subthemes occurred between those included in the Conservation and Representation of Community Values thematic groups with a total of 17 instances. Practically, this means that any of the five subthemes in the Conservation theme were attributed to the same quote as any of the three subthemes in the Representation of Community Values theme 17 times.

4 Discussion

We employed a mixed-methods approach to address questions of spatial variability as it affects ecosystem-service valuation, a process that can be applied and expanded upon in alternative future contexts. Using decision theory, deliberative exercises, and applied thematic analysis, we could examine how assessed tradeoff weights by stakeholders differed along the Massachusetts coastline. Our findings suggest that stakeholders in each of the three groups had markedly different preferences and shared social values; our quantitative and qualitative results indicate that policies formed with specific community values as a focal point may be better received than those formulated using generalized values (Benson et al., 2013; Ciftcioglu, 2021).

Group 1

Theme	Human Wellbeing	Scale of Impact	Conservation	Habitat Dynamics	Economic Issues	Representation of Community Values
Human Wellbeing	6	5	5	3	17	0
Scale of Impact		0	0	0	4	0
Conservation			6	2	4	3
Habitat Dynamics				0	1	0
Economic Issues					8	0
Representation of Community Values						0

Co-occurence frequencies: 0-4; 5-9; 10-14; 15-20

Group 2

Theme	Human Wellbeing	Scale of Impact	Conservation	Habitat Dynamics	Economic Issues	Representation of Community Values
Human Wellbeing	1	2	7	3	4	7
Scale of Impact		2	3	8	7	7
Conservation			9	4	11	17
Habitat Dynamics				3	3	9
Economic Issues					3	12
Representation of Community Values						7

Co-occurence frequencies: 0-4; 5-9; 10-14; 15-20

Group 3

Theme	Human Wellbeing	Scale of Impact	Conservation	Habitat Dynamics	Economic Issues	Representation of Community Values
Human Wellbeing	9	0	0	8	2	5
Scale of Impact		0	0	0	1	1
Conservation			6	2	0	0
Habitat Dynamics				0	1	4
Economic Issues					0	3
Representation of Community Values						1

Co-occurence frequencies: 0-2; 3-5; 6-8; 9-12

FIGURE 8
Co-occurrence frequencies heat map. Both the x- and y-axis display the six thematic groups determined during the applied thematic analysis. Lighter shades of green indicate fewer co-occurrences of the subthemes within the two thematic groups intersecting a cell while darker shades indicate higher frequencies (see legend). Quartile values were determined by dividing the highest co-occurrence frequency for each group and dividing that value into fourths (if the highest frequency did not yield integer values when establishing quartiles, the next highest divisible integer was used to establish an upper value). Empty cells, shown in grey, represent subtheme combinations that are already accounted for by another intersecting cell (for example, when read beginning with the rows, "Habitat Dynamics" and "Scale of Impact" co-occurrences are already counted at the intersection of "Scale of Impact" and "Habitat Dynamics").

4.1 Study limitations

Given the highly collaborative nature of deliberative processes, we anticipated that conducting workshops virtually would present both advantages and disadvantages. The high cost and extensive travel associated with in-person workshops, such as mileage reimbursement, hotel reservations, video-recording equipment, food, and supplies, can be costly and, thus, often a deterrent to voluntary participation; virtual workshops require less effort on behalf of the participant to attend and therefore theoretically should translate to higher recruitment rates. We, however, did not find this to be the case and experienced low recruitment rates, which we attributed to general fatigue regarding virtual events during this time–given that these workshops were conducted in December of 2020 during the coronavirus pandemic, widespread use of virtual platforms to conduct business and research seemed to decrease the willingness of stakeholders to participate in voluntary studies. These low recruitment rates resulted in the elimination of category 3 from this study, which would have provided not only data regarding the valuation of ecosystem services provided by the category's embayments but an additional group of thematic analysis results with which to compare inter-category discussions.

While Zoom proved to be a sufficient platform with which to host deliberative discussions, we did encounter minor technological issues that interrupted the flow of conversation or otherwise made it difficult for individual participants to engage in the deliberative activities. In similar past studies, in which deliberations were conducted in person, participants worked together to complete assessment tasks using interactive physical tools representing the ecosystem ESs under consideration. We recognize that had these workshops take place in person, our results may have differed due to a shift in participant dynamics (Tobin et al., 2020). Future studies implementing similarly collaborative studies using MAVT would likely be more effective if conducted in person.

4.2 Importance of value convergence for policymaking

Both the quantitative and qualitative analyses revealed divergent valuations of the ESs provided by salt marsh and eelgrass habitats at the category level. Our quantitative results, particularly the ESs attribute rankings at both the individual and group levels, portray unambiguous dissimilarity. Apart from a general study-wide consensus regarding the high relative importance of the Total Nitrogen attribute, results were highly disparate–for example, during the three salt marsh deliberations, Blue Carbon was given the lowest ranking by Group 1 but nearly tied with Total Nitrogen for most important in Groups 2 and 3 (Figure 5). The three eelgrass deliberations yielded a broad range of rankings for the Fish Abundance attribute: Fish Abundance was given a tied ranking for most important by Group 1 but was ranked as least or next to least important by Groups 2 and 3 (Figure 6). Conversely, standard deviation results from the pre- and post-deliberation surveys illustrate the consensus-generating nature of deliberative exercises. With three exceptions out of a total of 24 standard deviation changes recorded, as seen in Table 4, participants converged toward a given attribute's ranking. This outcome shows that the deliberative processes may create a space for in-depth discussion and interaction among participants, allowing new information and the experiences of others to influence and shift their own values (Allen et al., 2021; Saarikoski and Mustajoki, 2021).

The output of deliberative processes, particularly when they result in value convergence, can assist environmental managers to justify decisions related to policy prioritization and enactment. For example, Group 1 placed monetary subthemes at the forefront of deliberations, as exhibited by their emphasis on the commercial enterprises and food source subthemes. This suggests that policies written from the perspective of direct human benefits rather than ecological considerations may receive more support. This group was also unique in placing Fish Abundance as their highest priority for the eelgrass ecosystem–special attention should be given to the ecological and economic benefits this service provides to the category's local communities (Pascual et al., 2022). In addition, environmental managers can assess the relative desirability of hypothetical management future choices by using MAVT (Borsuk et al., 2019). The overall social value of the ecosystem services provided for various hypothetical management future choices hinges upon the projected attribute levels and the weights assigned by the stakeholders. Future studies may need to invest more resources in projecting the provision of ecosystem services under different management future choices.

In addition, our analysis shows the importance of including the public in the environmental decision-making process. Group 2's discussions centered around the perceived needs and desires of the public; their most frequently recorded subthemes were commercial enterprises, public engagement, and public support. Intentional citizen participation in environmental decision-making and structured solicitation of local perceptions is likely necessary for long-term success, as is the need to clearly communicate the systematic implications of a policy decision, especially as they relate to local economies. Therefore, we need to invest more resources in participatory valuation methods that engage citizens and represent both their values and subjective judgment in environmental decision-making (Beyers and Arras, 2021; Dimitrovski et al., 2021).

4.3 Importance of spatial variability for environmental management

Deliberative valuation has previously been used to identify shared social values and allow stakeholders to express their willingness to prioritize certain ESs above others (Orchard-Webb et al., 2016; Mavrommati et al., 2020). This study utilized DMCE to elicit shared values from stakeholders of statistically defined geographic locations, highlighting the variability of valuation along the Massachusetts coastline. Utilizing a deliberative format rather than a questionnaire or survey-based approach allowed us to observe the nuances of how stakeholders in each group interacted with their local ecosystem and benefited from their continued health (Kenter et al., 2016). By presenting identically designed workshops to groups of stakeholders that utilize spatially delineated landscapes, we were able to identify the need for community-led policy formulation designed with a specific geographic region at the center rather than broad measures drafted for large, multi-faceted areas of coastline.

By limiting our investigations to specific habitats, eelgrass beds, and salt marshes, we could provide category-specific data to stakeholders, enabling them to contextualize potential changes in the attributes we examined. Specific drivers clustered embayments with similar attributes together, making it easier for decision-makers to identify priority restoration and conservation actions specific to those embayments to protect vulnerable resources, reduce stressors, and improve habitat conditions. This information will assist in setting realistic goals for improving the extent and condition of habitats in various embayments.

4.4 Opportunities for future research

A potential area for further study is the role of the individual within deliberative groups. Our observed lack of a relationship between total verbal contributions and an individual's convergence with group values suggests that the content of participants' contributions holds more power in a deliberative setting than their willingness to consistently engage in discussion. Within the context of this study's workshops, participants that spent the most time silently considering the values of others were more likely to converge toward final group results. Several potential explanations for this phenomenon exist in deliberative literature; variation in receptivity to alternative opinions with regard to participant age and gender, the volatile variable of personality, and an individual's previous experience with deliberation in a formal or informal context are some of those often cited (Steiner, 2012; Suiter et al., 2014). The ability of an individual or individual(s) to dictate the direction and results of a deliberative discussion is a variable worth exploring further.

The effectiveness of investments in habitat restoration depends on the willingness to gain stakeholders' support. Employing decision-making frameworks that actively engage stakeholders and provide tools for science communication, building social learning, and eliciting environmental priorities is essential. We suggest that deliberative valuation techniques provide a basis for assessing ESs tradeoffs in a manner that critical research questions such as spatial variability could be explored. Quantitative and qualitative analysis of the workshop outputs shed a light on the reasoning behind participants' choices within a process in that participants build their understanding and appreciation of other values resulting in shared social values and value convergence in individual values. More applications are needed to explore deliberative valuation techniques further and find alternate ways to engage the general public effectively.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the University of Massachusetts Boston Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

Research performed under the direction of GM (Primary Investigator) by JL-M, NS-S, AK, and SBR in collaboration with PAD and PV. Manuscript written by JL-M under the guidance of GM, PAD, and PV. Workshop design and implementation by JL-M, GM, PAD, and PV. Thematic analysis performed by JL-M, NS-S, AK, and SBR. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

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Going with the flow: the supply and demand of sediment retention ecosystem services for the reservoirs in Puerto Rico

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Impounding surface waters in reservoirs is a major mechanism for providing water for human consumption, including potable water, hydroelectric power, and industrial uses. Building reservoirs incurs environmental and social costs, and therefore safeguarding their effectiveness and longevity is a concern of clear public interest. One factor that affects the longevity of reservoirs is sedimentation, a process exacerbated by land use conversion in upstream watershed areas. Despite the economic importance of preventing sedimentation in existing reservoirs, few consumers are aware of the natural features that provide sediment retention services and the relevance of their conservation in their daily lives. Moreover, managing for landscape level sediment retention services is challenging due to a lack of clarity regarding supply and demand flows that transcend watershed boundaries and jurisdictions. Our study seeks to bridge these gaps by characterizing the flow of sediment retention services to reservoirs and link these services to the specific consumers that benefit using a socio-ecological network (SEN) framing. We conducted this study on the island of Puerto Rico (PR), the population of which is heavily reliant on reservoirs as a primary water resource, while experiencing severe and chronic reservoir sedimentation problems. Our study models avoided sediment export, and the costs were averted thanks to this service. We characterized protection as opposed to vulnerability of these sediment retention services by estimating the proportion of natural areas under some form of legal conservation status and the level of landscape fragmentation. We frame these services as an SEN by using water distribution lines as links to estimate the number of beneficiaries and their location relative to the reservoir's water source. Our results identify watersheds with conservation needs, their beneficiaries, and where within those watersheds to prioritize conservation efforts to safeguard access to clean water in PR. More broadly, our study provides a model case study for establishing supply and demand service flows of water purification services and demonstrating the utility of mapping socio-ecological networks of service flows in order to justify conservation policies based on ecosystem services.

KEYWORDS

ecosystem services, sediment retention, reservoirs, socio-ecological networks, Puerto Rico

1 Introduction

Reservoirs are among the most important sources of freshwater for human consumption, with uses ranging from household to industrial consumption, agricultural irrigation, hydropower, and flood control. With population growth and the ever increasing consumption patterns, the demand for freshwater has led to the impoundment of many of the world's rivers and tributaries. Today, it is estimated that over 60% of the major rivers worldwide are interrupted by dams, and often at the expense of altering the river's connectivity and ecological function (Grill et al., 2019), including changes in flow regime (Poff and Zimmerman, 2009), geomorphology (Chong et al., 2021), and the migratory routes of aquatic fauna, all leading to freshwater biodiversity decline (Turgeon et al., 2019). Given their importance across the major sectors of society, and the environmental costs that they represent, ensuring the effective functioning and longevity of existing reservoirs (and hence preventing the need for developing new dams) should be a key societal priority.

The most important driver of reservoir lifespan decline is sedimentation (Podolak and Doyle, 2015). Sedimentation is largely caused by natural processes in the upstream watersheds of reservoirs, including erosion, landslides, and instream deposition (Schleiss et al., 2016); however, anthropogenic land uses such as deforestation, agriculture, and urbanization can also accelerate reservoir sedimentation rates (Gellis et al., 2006; Yuan et al., 2015; Attulley et al., 2022). Conversely, natural areas, such as forests and wetlands, have the capacity to mitigate erosion and retain eroded sediments, helping prevent their deposition in streams and rivers (Hammel et al., 2015; Guerra et al., 2016). The conservation of these sediment retention ecosystem services (ES) should therefore be incorporated into reservoir management strategies, which often rely solely on reactive and costly approaches such as reservoir dredging.

Incorporating watershed-scale ES management for reservoir longevity requires clearly defining the extent of the services and the beneficiaries of such services. Accordingly, an increasing number of studies have focused on mapping and identifying the service flows from ES supply and demand (Wei et al., 2017). In the context of water quality, ES supply consists of upstream to downstream watershed-scale hydrological processes including evapotranspiration, infiltration, and runoff generation, which influence water purification and erosion control. Mapping the extent of hydrological ES supply has been advanced by remote sensing and geographic information system technology that facilitates access to spatially explicit data on topography, land cover, soil, and climate. These data can be used as inputs for existing hydrological modeling approaches (Renard et al., 1997; Borselli et al., 2008), which in turn have been incorporated into user-friendly platforms readily accessible to ES managers (Hamel et al., 2015; Sharp et al., 2020).

For ES demand, clearly defining the spatial relationships related to hydrological ES flows is an important step toward coordinated governance strategies that explicitly link the diverse set of influential actors and users for a more strategic watershed management. While the mapping of ES supply is now more accessible than ever, the governance capacity of ES flows has been challenging due to a lack of landscape-level policy support systems and tools, as well as the difficulty of communicating the social and economic importance of landscape-level ES to relevant stakeholders and end-users (De Groot et al., 2010).

One way to do so is to frame the system of services as a network graph, with nodes and links (or edges in network terminology) connecting landscapes to people via a mix of natural and constructed features (Felipe-Lucia et al., 2021, Figure 1). This approach to describing the relational components of coupled systems exemplifies a socio-ecological network (SEN) framing (Sayles and Baggio, 2017; Sayles et al., 2019; Felipe-Lucia et al., 2021). Incorporating SEN framing allows for linking the spatial and scalar dimensions of the functions that support the landscape production of ES (e.g., river stream networks) to the scales of demand and consumption for the final services and their linkage to human populations (i.e., pipelines connecting water sources to households). There is a need for the standardization of ES structures and for mapping ES social and economic values (De Groote et al., 2010). SEN framing facilitates the standardization of dyadic components of ES flows (nodes and ties) and also the mapping of service flows to end-users. This is in turn important for valuing tradeoffs from different policy decisions related to planning infrastructure and land use that impact landscape functions.

In the case of sediment retention services, the important nodes are the landscape units (watersheds and micro-catchments), the reservoirs, the filter plants, and the service areas to consumers. They are linked by flows, or edges, via natural features such as streams in the case of the landscape-to-reservoir networks, which then connect to the constructed features of pipe networks to filter plants and then to end-users. Applying an SEN framework can help identify the natural and human components of ecosystem supply and demand, allowing researchers to focus more concretely on sometimes hard to conceptualize inter-relationships. In doing so, it helps inform management within complex systems, especially questions of governance in spatially mismatched systems (Bodin et al., 2019; Sayles et al., 2019; Wang et al., 2019), as is the case with sediment retention and other hydrological ecosystem services.

In this study, we will use the SEN framework to fully characterize the sediment retention service flows for reservoirs in the Caribbean Island of Puerto Rico (PR). The reservoirs in PR are the primary water resource for the majority of PR's population (Ortiz-Zayas et al., 2004; PRDNER, 2008a; Quiñones, 2022). They are also important for hydroelectric power generation, flood control, fisheries, and recreation (Ortiz-Zayas et al., 2004). Most of PR's reservoirs have experienced significant capacity loss due to sedimentation (Ortiz-Zayas et al., 2004; PRDNER, 2008b; Quiñones, 2022). Reservoir capacity losses in PR due to sedimentation range from 12% to 81%, depending on topography, rainfall patterns, and anthropogenic impact (USGS, 2019).

The effects of climate change (droughts, more frequent hurricanes, and floods) could potentially exacerbate reservoir capacity loss in the future, increasing the need for preventative watershed-scale sediment management strategies. For example, in PR, the recent hurricanes Maria, Irma (2017), and Fiona (2022) contributed to a severe capacity loss for many of the island's reservoirs, including a 16% capacity reduction for Dos Bocas, one of the most important reservoirs of the island, rendering its remaining lifespan to 37 years (Quinones, 2022). Moreover,

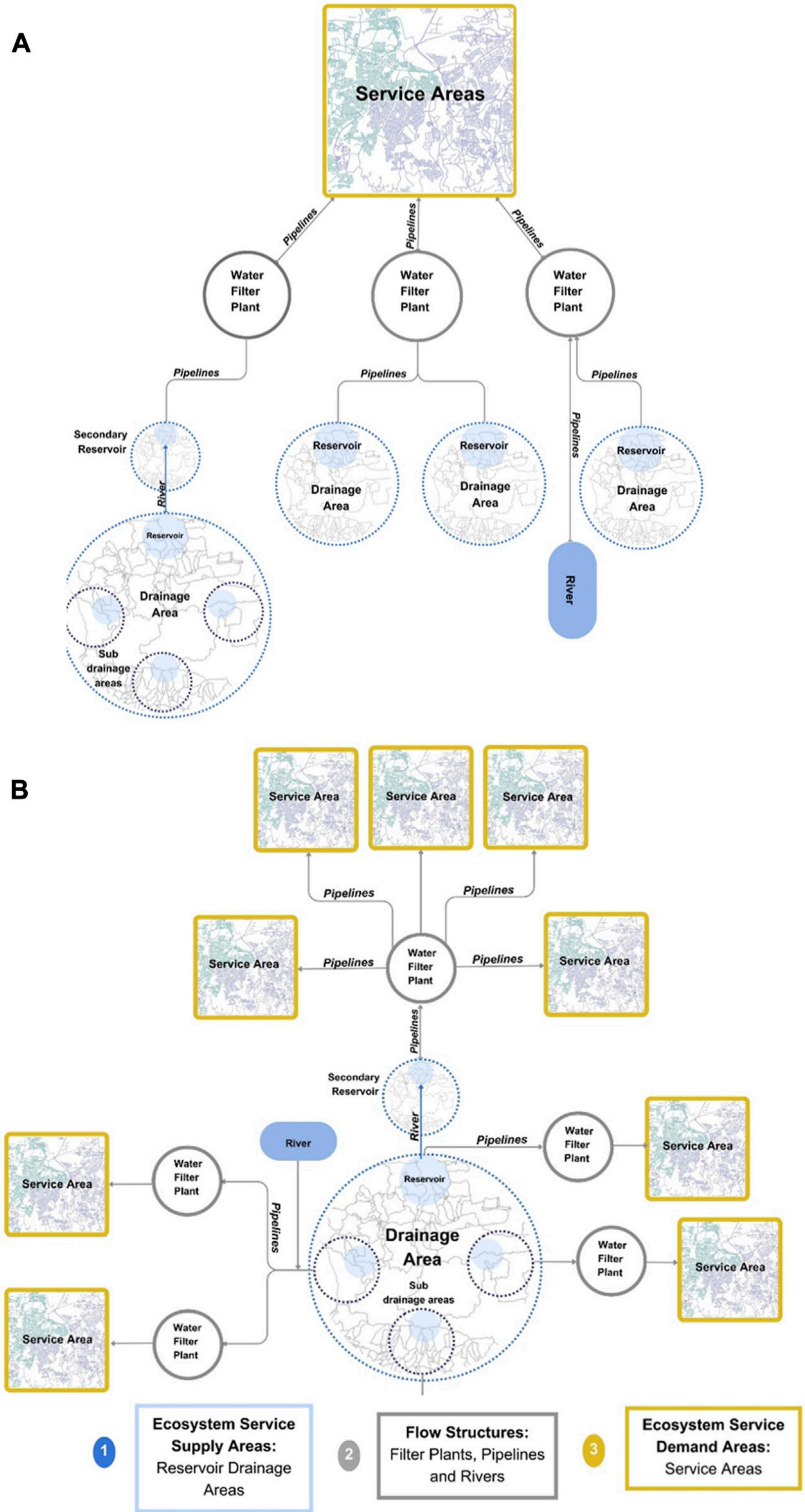

FIGURE 1
Conceptual representation of the sediment retention ecosystem service supply and demand flows using an SEN approach. Panel **(A)** represents the network of a single service area, which represents the location of end users and their linkages to several reservoirs and their respective watershed areas. Panel **(B)** represents the network of a single reservoir's watershed area and its linkages to multiple service areas. We present an example of each of these derived from our data in Figure 6.

88 million dollars of the Federal Emergency Management Agency (FEMA) disaster recovery funds for PR have been allocated for the dredging of another important reservoir that became severely affected due to recent hurricanes (FEMA, 2022a). The critical state of the island's reservoirs makes them especially vulnerable to droughts, as evidenced in the period of 2014–2016, when a severe drought compromised access to potable water on the Island, requiring the implementation of rationing practices to households during the summer months and resulting in severe agricultural losses (PRDNER, 2016). These events show that PR's water resources are vulnerable to climatic events and should be prioritized for preventive management. The recent influx of federal resilience planning (FEMA, 2022b), and more recently for nature-based solutions (NOAA, 2023) to PR, suggest the need for empirical data and strategies to support effective prioritization and management.

Our specific objectives for this project are as follows: 1) to quantify and value the sediment retention services upstream of important reservoirs for water consumption, 2) to determine the location of the beneficiaries of these services and create service-shed network maps illustrating the flows of supply to demand, and 3) to determine the vulnerability of these service flows by looking at the level of legal protection and/or fragmentation of natural areas. Addressing these objectives would help inform prioritization for watershed level management of the reservoirs in PR. Moreover, by framing these objectives around an SEN approach, this study provides practical steps for operationalizing the study of ES flows and helps inform their management. While the outputs of this study most directly inform ES flow management by environmental and water resource agencies, authorities, and engaged advocacy groups, our study also provides information that can aid in creating greater general awareness about ES flows, what areas are important for conservation, and who benefits from them. The connection of water consumer geographies to relevant ES landscape units can be useful for a broad swath of the society, ranging from concerned individuals to clients of water utilities, as well as grassroots organizations interested in community-based planning and engagement.

2 Methods

2.1 Study site

Puerto Rico is a Caribbean island with an estimated 3,221,789 inhabitants, a population density of 960 people per square mile, and a total land area of 3,424.32 square miles (US Census, 2022, data as of June 2022). Annually, temperature averages range from 22 to 25°C in the mountains to 24–27°C in coastal areas (USGS, 2013). A central mountain range divides the north and south ends of the Island, creating distinct rainfall patterns. Rainfall in the most humid areas of PR can reach 169 inches/year (4292.6 mm/yr), whereas in the most arid regions, it averages 30 inches/year (762 mm/yr) (USGS, 2016). Overall, the island has a tropical climate with local microclimatic variations due to topography and trade winds.

From the environmental governance perspective, PR is well-positioned to develop landscape-level management efforts compared to other US jurisdictions with more decentralized planning systems. A centralized Puerto Rico Planning Board was created during the New Deal and aimed to create comprehensive economic and land use planning through a centralized government entity (Howell, 1952; Pico, 1953). Water utilities and sewer systems are also centralized under a single utility, Puerto Rico Aqueduct and Sewer Authority (PRASA), the Puerto Rico Department of Natural and Environmental Resources (DNER) has been the island's resource and pollution regulator since the 1970s, and a Joint Permit Regulation for Construction Works and Land Use issued by the Puerto Rico Planning Board governs land use permit under the Puerto Rico Planning Board Organic Act (1975) (Diaz-Garayua and Guilbe-Lopez, 2020), but other functions, e.g., administering local collections and parcel inventories, are part of the Puerto Rico Municipal Revenue Collections Center (CRIM). Within that context, the 1991 Autonomous Municipalities Act provided significant power for some planning and permitting and revenue activities, as well as traditional roles with local infrastructure (e.g., municipal roads) to many municipalities, leading to greater fragmentation in decision-making. However, within this system, much of the coordination and informatics for planning is still managed by the planning board, which was authorized in 2004 to create a Puerto Rico Land Use Plan, harmonizing land use classification and zoning, in conjunction with existing municipal plans throughout the entirety of PR. The plan was enacted in 2015 with land use classifications, and specific zoning is contained in the Territorial Ordainment Plan for each municipality where applicable (USGS, 2015). The combination of partial Municipal planning control, strong mayoral political power, private property rights and interests, and a mix of statewide planning authorities means that Puerto Rico is somewhat polycentric in terms of the landscape management scale, but amenable in structure and size to comprehensive landscape approaches.

These approaches may be collaborative or polycentric (Berardo and Lubell, 2016, Ansel and Gash, 2018), but they need to define salient landscape scales and areas if collaborative planning is going to operate. Special legislation and participation in national programs has created landscape level watershed efforts in the environmental quality realm, such as the San Juan Bay Estuary (SJBE) program. These efforts recognize challenges for the integration of local and community decision-making into the landscape/watershed context, but face the complexity that watersheds are governed by diverse domains intersecting with planning and infrastructure, not just environmental interests. Within this context, the scales and geographies of ES networks and flows must be defined if they are going to be governed, regardless of whether the policy strategy is centralized or polycentric. However, the collaboration to build structures for landscape governance may require creating forums and by-ins from actors at different scales and domains who can recognize their interdependent interests in governing ES flows, which requires their definition and mapping to resolve information asymmetries. This larger need was identified in the Puerto Rico Water Plan (PRDNER, 2008a), which has not been executed, and is part of the drivers of the legacy challenges to the Puerto Rico water sector.

We applied a watershed scale analysis for this study to help inform water quality governance, focusing on reservoirs supplying water for consumption. Puerto Rico has 36 reservoirs that have been

TABLE 1 Sediment retention service is quantified as avoided sediment exports and avoided dredging costs for the watersheds draining to reservoirs in Puerto Rico. * Loiza is also called Carraizo.

Reservoir	Watershed area (km^2)	Avoided export (tons/yr)	Avoided export per area (tons/km^2)	Avoided cost (USD/yr)
Carite	21.47	369,887	17,229	$144,253
Cerrillos	45.09	6,627,713	146,986	$3,512,921
Cidra	21.04	291,545	13,859	$165,839
Dos Bocas	218.09	15,479,426	70,977	$39,387,024
Fajardo	27.37	2,602,034	95,083	$1,614,172
Garzas	15.86	1,069,718	67,453	$1,324,658
Guajataca	60.46	847,084	14,010	$1,048,077
Guineo	4.24	249,703	58,846	$202,981
La Plata	445.98	25,103,703	56,288	$16,082,985
Loco	21.84	2,255,803	103,284	$1,595,812
Loiza*	497.87	22,039,978	44,268	$11,473,798
Luchetti	45.06	6,945,401	154,147	$7,868,101
Matrullas	11.57	539,882	46,671	$541,416
Patillas	66.65	7,382,188	110,757	$3,571,233
Portuguez	27.10	3,661,004	135,115	$1,911,653
Prieto	24.60	2,845,787	115,667	$2,029,552
Rio Blanco	25.93	385,735	14,874	$153,765
RAN	21.73	3,244,650	149,336	$2,634,199
Toa Vaca	57.49	6,507,227	113,187	$5,155,293
Valenciano	40.04	1,396,686	34,878	$1,027,483
Vivi	16.79	1,846,721	109,984	$1,197,390
Max	497.87	25,103,703	154,147	39,387,024
Min	4	249,703	13,859	144,253
Mean	85	5,318,661	78,662	4,887,743

used directly for services such as hydroelectric power generation, irrigation, and water consumption, as well as indirect services, such as flood control and recreation (Ortiz-Zayas et al., 2004; Quiñones, 2022). It is estimated that 70% of the potable water handled by the PRASA comes from reservoirs (Ortiz-Zayas et al., 2004; Quiñones, 2022) and that 96% of the residents of PR are served by PRASA (USGS, 2018). Most of the reservoirs are located in the central mountainous region to take advantage of the abundant rainfall in this area (Ortiz-Zayas et al., 2004). All reservoirs have seen reduction in their capacity due to high sedimentation rates, representing an important issue for water resource conservation in the Island (Ortiz-Zayas et al., 2004; Quiñones, 2022). Out of the existing reservoirs, we selected the trends on 20 reservoirs for detailed study (Table 1) due to their current importance for water consumption, excluding those that are no longer in use or that are primarily used for other purposes. We also included in our study a small artificial lagoon (*Retencion Acueducto Norte*, RAN Table 1), which is downstream from one of the major reservoirs (Dos Bocas) and which contributes water to one of the most important pipelines of the Island the "*Acueducto Norte*" (Ortiz-Zayas et al., 2004). The selected reservoirs had watershed areas ranging from 4 to 498 km^2 (Table 1). The sediment retention supply calculations focus on these watershed areas (entire upstream drainages including all stream tributaries) and also on the micro-catchment areas (the drainage areas of individual tributaries) within these larger watersheds (Figure 5). We conducted our analysis at both scales in order to provide concise summaries and valuations broadly (watershed scale) and create maps to identify areas within the watersheds that provide the most services currently and that could be targeted for conservation (micro-catchment scale).

2.2 Estimating sediment retention service supply

To estimate sediment retention ecosystem services, we used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) modeling platform. InVEST is a suite of open-source modeling software that generates spatially explicit estimates of ecosystem services which can then be used for environmental management applications (Natural Capital Project, 2022). We applied the sediment retention (SR) model (Hamel et al., 2015; Sharp et al., 2020) which maps the generation and delivery of sediments from overland erosion to the stream. The model computes the annual soil loss from each pixel (uslei) and the sediment delivery ratio (SDRi), that is, the proportion of the soil loss that was not retained by vegetation and topographic features and thus reached the stream. The product of the two values equals the sediment export from a given pixel, measured in tons·ha−1yr−1. Once in the stream, the sediment is assumed to reach its outlet, and no in-stream processes are modeled.

The annual soil loss on pixel i, uslei, measured in tons·ha−1yr−1, is estimated using the Revised Universal Soil Loss Equation (RUSLE1; Rendard et al., 1997), which is a widely used and validated erosion model predicting annual soil loss based on runoff, slope, and land cover (Rendard et al., 1997). In particular, RUSLE is a product of five values: Ri—rainfall, erosivity Ki—soil erodibility, and LSi—slope length-gradient, estimated from elevation relationships (slopes) of a given pixel and its neighboring area using multiple flow direction algorithms,

Ci—cover-management factor (usle_c in the biophysical table)

Pi-—support practice factor (usle_p in the biophysical table)

In turn, SDRi, a proportion, is a function of SDRmax, maximum theoretical SDR (chosen based on the input for the entire model), connectivity index, and two other calibration parameters chosen for the model (Borselli's IC0 and k), which define the function describing the growth of SDR over the connectivity index, which is an S-shaped increasing function. Lower k defines a steeper growth of SDR, and lower IC0 produces a function with higher overall SDR values. The connectivity index, similarly to the slope length-gradient factor, uses multiple flow direction algorithms and captures slope relationships, but in contrast also accounts for the cover-management factor values of pixels. This index hydrologically links the overland sources of sediment to streams (sediment sinks), with its higher values corresponding to higher connectivity, for example, due to the sparse vegetation or higher slope, or *vice versa*. Once the sediment export is estimated as the product of uslei and SDRi, the retained sediment amounts for each pixel can also be measured as the difference between the sediment generated (uslei) and subsequently exported from the pixel.

For this study, the erosivity raster (R-factor) was acquired from NOAA Coastal Services Center (2014b) and converted from US customary into System International (SI) units by multiplying the raster values by 17.02, as detailed in Appendix A of the USDA RUSLE handbook (Renard et al., 1997). Soil erodibility raster (K-factor) was tabulated from the gNATSGO database (USDA NRCS Soil Survey Staff (2021a) and similarly multiplied by 0.13 to convert into SI units (Renard et al., 1997). The biophysical table for the SDR model contained usle_c and usle_*p*-values for each land use and land cover (LULC) code and was derived from previous studies (Wischmeier and Smith, 1978; Stone and Hilborn, 2012) and adapted from Smith et al. (2017), which conducted the most recent modeling effort for ES in Puerto Rico. For the land use and land cover layer, the NOAA 2010 Coastal Change Analysis Program (C-CAP) 30 Meter Land Cover of Puerto Rico raster was used (National Oceanic and Atmospheric Administration Office for Coastal Management, 2022). To our knowledge, this is the most recent LULC layer for the Island. It classifies LULC in 23 classes described in detail in the NOAA Office of Coastal Management (2022). A digital elevation model (DEM) raster was required, and for this we used the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, 2019) data. The ASTER DEM was corrected by filling in sinks (using the fill tool in ArcGIS Pro; Esri, 2022a), and the output stream maps from the InVEST model were confirmed to be consistent with existing stream shapefiles (USGS, 2017). The calibrating parameters were set to default values according to InVEST guidelines (Sharp et al., 2020), and they were as follows: threshold flow accumulation (number of pixels)—100, Borselli K parameter (which was tested at values ranging from 1 to 3, with 0.5 increments; see the validation/ calibration section), Borselli IC0- 0.5, maximum SDR (proportion) set at 0.8, and maximum L value 122.

Previous validation studies using the InVEST SR model have found support for the use of the tool for the first-order ES assessment to prioritize and rank areas for conservation (Hamel et al., 2015). The use of local data for model validation and calibration is recommended to improve the performance and accuracy (Hamel et al., 2015; Hamel et al., 2017). Our calibration and validation process is described in the next section.

2.3 Sediment Retention Service Model Validation and Calibration

To validate the outputs of the InVEST SR model, we compared the model's sediment export estimates from 22 watersheds draining into the reservoirs to the measured values of average annual sedimentation rates on the same reservoirs (Quiñones, 2022). These values were compiled as Mm^3 per year, so we converted our tons per year estimates to this unit using the steps detailed in Supplementary Material S1. In addition, the InVEST SR model was tested with different values of the parameter k_b, which has been found in previous studies to be the most sensitive to variation (Anjinho et al., 2022). We tested the model with values ranging from 1 to 3, with 0.5 increments, and determined their relative performance using a coefficient of determination criteria (Rauf and Ghumman, 2018; Anjinho et al., 2022). The coefficient of determination values ranged from R^2 = 0.72 for k_b = 1 to R^2 = 0.77 for k_b = 3. All the tested models' performances were classified as "good" according to criteria from previous studies validating observed vs. modeled sediment exports (Rauf and Ghumman, 2018; Anjinho et al., 2022). While the sediment estimates correlated to observations, the estimated values ranged in magnitude based on the k_b parameter used (the higher the k_b, the higher the value, SM2). Because the InVEST SR model only accounts for overland erosion, and does not include other potential sources of sedimentation (e.g., gully erosion, landslides, and bank erosion), we expected our sediment export estimates to be lower in magnitude than the observations. This was consistently the case for our lower bound estimate (k_b = 1).

We also compared our value estimates with those of previous studies on overland erosion rates. Ramos-Sharron and Figueroa-Sanchez (2017) estimated the overland sediment export from coffee farms in the Luchetti watershed which ranged between 14,000 and

29,500 Mg per year (or 15,432 and 32,518 tons per year). By comparison, our model estimated a range of total overland sediment exports in the same watershed of 40,789–130,599 tons per year, as shown in Supplementary Material S2. Considering that coffee farms comprise only a portion of the Luchetti watershed area, our lower bound estimates (k1) may be considered to be within similar value ranges. Another example comes from the Canovanas watershed. We estimated it to have an overland sediment export range between 38 and 220 tons/km2/year (Supplementary Material S2), while an empirical study for this same watershed (Larsen, 2012) estimated the export to be 41 metric tons/km2/year from the overland erosion component of the sediment budget (in that study defined as slopewash and tree throw). We determined from these comparisons, as well as our validation analysis, that our lower bound estimates (k_b = 1, SM1) were the most credible based on empirical observations. Therefore, our descriptive analyses will focus around these values. However, for details of the higher bound value estimates, see Supplementary Material S2.

2.4 Dollar valuation of sediment retention services

We estimated the present dollar value for the avoided sediment export using the formula described in Sude et al. (2011) (Equation 1):

$$Value_{SRi} = SR_i \; X \; MC,$$

where SR_i is the sediment prevented from entering the water system per pixel and MC is the cost of sediment removal. We estimated the value of sediment removal using the existing estimates of sediment dredging costs. While the actual costs of sediment removal can vary based on the size of the project, the dredging technique, and the sediment disposal approach (Anchor, 2019), we used an estimate of $8 m^3, which has been applied in previous studies for calculating reservoir sediment management in the US (Smith et al., 2013). We adjusted the value to $8.64/ton using a conversion factor of 1.08 ton/m^3 based on the bulk density estimates of sediments in a reservoir in PR (Soler-Lopez et al., 1997).

However, this is a lower bound, as recent value estimates range between $8 and 60 per m^3, considering that the costs of site preparation, management, and sediment disposal are taken into account (Anchor, 2019). In addition, recent estimates from a reservoir dredging project in PR suggest a cost of up to $26 per ton (FEMA, 2022a), so our cost per ton estimate is a lower bound, conservative value. We extrapolated these costs over a 20-year period, applying the equation mentioned previously plus a discount rate of 3% (0.03) per year, based on the Office of Management and Budget guidelines (CEA, 2017), and those used in other similar estimates, which may include rates of 7% in some instances, although some newer recommendations around the social costs of carbon, for example, are using 2%–3% discounting rates (USEPA, 2022). We then estimated the net present value of the average cost per year after adjusting for the discount rate. Our analysis does not include estimates about rates of inflation for infrastructure projects, which should be considered in future studies, or when adopting the final valuation policies.

2.5 Vulnerability assessment of sediment retention services

To estimate the vulnerability of the sediment retention service, we characterized our study watersheds in terms of fragmentation and level of protection. Landscape fragmentation may lead to alterations in ES supply and demand flows (Mitchell et al., 2015). In the context of water purification and runoff reduction, landscape fragmentation can disrupt flow patterns, interrupting the retention capacity of natural areas when they are interspersed with anthropogenic land uses (Mitchell et al., 2015). In addition, we argue that once a landscape is fragmented, it becomes more vulnerable to urbanization. This is because fragmentation leads to a reduction in habitat quality, biodiversity, and ecological function (Mullu, 2016), all of which are factors that are taken into consideration when granting or denying development permits in PR (Puerto Rico Law 241 1999; Puerto Rico Law 416 2004). In addition, once a natural area is fragmented by a road or infrastructure, it becomes more connected to the larger urban infrastructure and more amenable for further development, an effect termed "induced growth" (Cervero, 2003). Conversely, in protected areas, where there are formal legal and planning protections, there would be less vulnerability to fragmentation and to the loss of ES flows.

To quantify fragmentation, we used the 2010 National Land Cover Database of USGS. We estimated at the landscape and class level, the edge density, number of patches, and patch density using the *landscapemetrics* package in R (Hesselbarth et al., 2019). The landscape metrics were calculated at the micro-catchment and the watershed scale. To quantify vegetation fragmentation, the edge density and patch density values of the land cover classes associated with vegetation were summarized using the weighted average method. The grassland, mixed forest, scrub, palustrine forested wetland, palustrine scrub wetland, palustrine emergent wetland, estuarine forested wetland, estuarine scrub wetland, and estuarine emergent wetland values were weighted as a function of the percentage of land per class (Equation 2).

$$CM\,jw = \sum (CMi * PLAND/100),$$

where CM_{jw} is the class metric weighted value for a site j, CM_i is the value per class metric, and *PLAND* is the percentage of the land cover by the class.

To estimate the level of protection, we used the Protected Areas Database of the United States (PAD-US) 3.0 (USGS & GAP, 2022), A protected area under the PAD-US database is one: "*Dedicated to the preservation of biological diversity and to other natural (including extraction), recreation and cultural uses, managed for these purposes through legal or other effective means*" (USGS & GAP, 2022). They include land with state or federal protection status (e.g., wilderness areas, national monuments, and area of critical environmental concern) and long-term easements and agreements (USGS & GAP, 2022).

We used the ArcGIS Pro Analysis tools to estimate the percentage of protection per watershed area and micro-catchment. A summary of the steps followed to characterize service supply, protection, and fragmentation is presented in Figure 2.

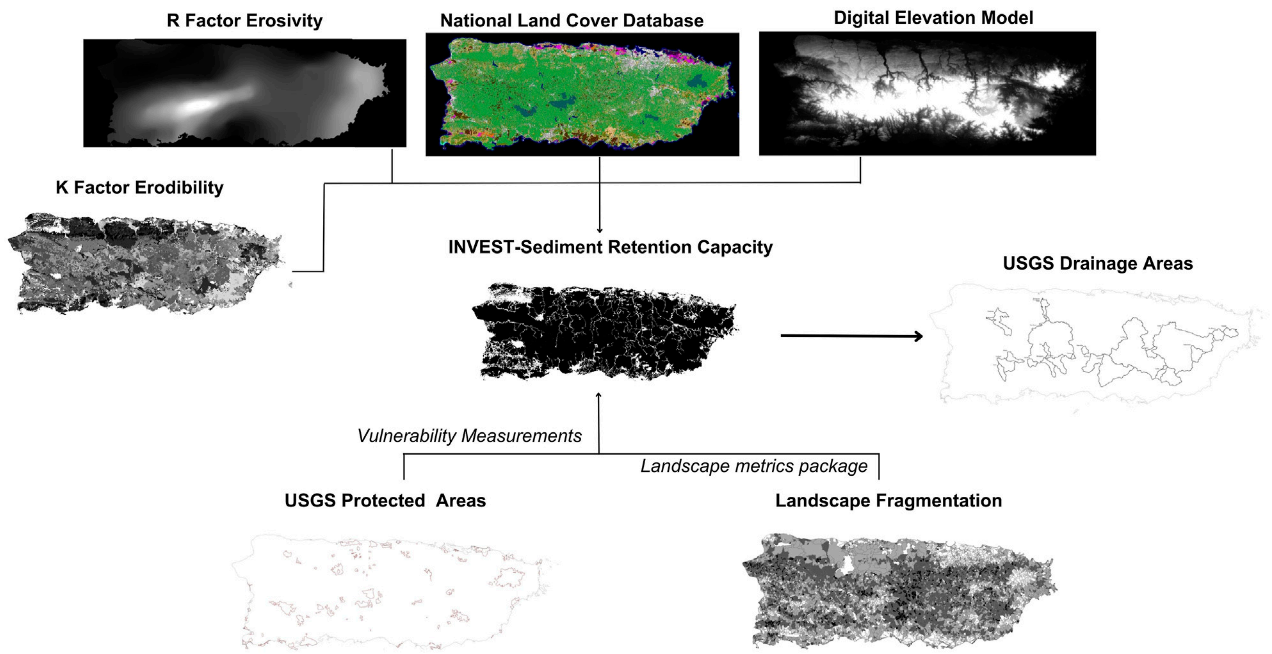

FIGURE 2
Summary of steps followed and data inputs used for the characterization of sediment retention service supply and vulnerability.

2.6 Estimating sediment retention service demand using an SEN framing

A combination of spatial and non-spatial data was used to delineate the service areas and estimate the population served to measure the ES demand. First, the watershed areas and reservoirs were defined as the supply nodes. For this study, the reservoir watershed areas were acquired from the National Water Information System of the United States Ecological Survey (USGS, 2023). The service areas were defined as the demand nodes, and the streams and pipe networks were defined as edges connecting the demand and supply nodes. Furthermore, intermediate structures such as water filtration plants and pipeline pressure zones were used to trace the ES flow along the network.

To identify the service areas associated with the water reservoirs, we joined the 2022 water quality reports provided by the Puerto Rico Aqueduct and Sewer Authority (PRASA, 2021) and the Safe Drinking Water Information System (SDWIS) datasets from the United States Environmental Protection Agency (USEPA, 2023). Second, to map the service areas' spatial extent, we used the ArcGIS Pro 3.0 spatial analysis tools to join the filter plants, pipelines, and pressure zone network layers from the Puerto Rico Aqueduct and Sewer Authority (Esri, 2020). We summarized the population and number of households within each service area using the ESRI USA Census 2020 Redistricting Blocks layer that joins the U.S. Census Bureau population information and the 2020 TIGER boundaries for Puerto Rico (ESRI, 2022b). Further details about the specific process used to undertake this analysis are provided in Supplementary Material S3.

We compared our service area population estimates with the estimates published online by the PR Aqueduct and Sewer Authority for the reservoirs that they administer (PRASA, 2023). While the PRASA estimates capture the demand for the reservoirs within their supply system, the data do not provide an estimate of demand for reservoirs not administered by PRASA but that also provide water for consumption. In addition, the data do not include location information beyond a list of municipalities, making it difficult to detailed comparison of user demand. Therefore, our approach is intended to 1) provide a more accurate location of service characterization for PR and 2) test the SEN approach for estimating water use demand in locations where specific consumer data are not readily available. Figure 3 shows the workflow followed for the service demand estimates.

To estimate the actual water demand per household, we used the daily *per capita* domestic use in PR estimated at 98 gallons (0.37 m^3) (Molina Rivera and Irrizary-Ortiz, 2021). We then extrapolated these values to a year, for an estimated annual *per capita* use of 135 m^3. Since the average population per household in PR is 2.74 people (US Census, 2022), this leads to an estimated water use of 370 m^3 per household/yr. We multiplied this number by PRASA clients served (when available) or SEN household estimates to estimate the household water demand (Mm^3/yr) for each system. For reference, we also include the reservoirs' current capacity based on data obtained by Quiñones (2022) (SM1) for comparison with our demand estimates.

3 Results

The watershed scale mean avoided sediment export was 5,318,661 tons/yr and ranged from 249,703 tons/yr to 25,103,703 tons/yr. The watershed with the highest sediment total avoided export was La Plata, and the one with the lowest

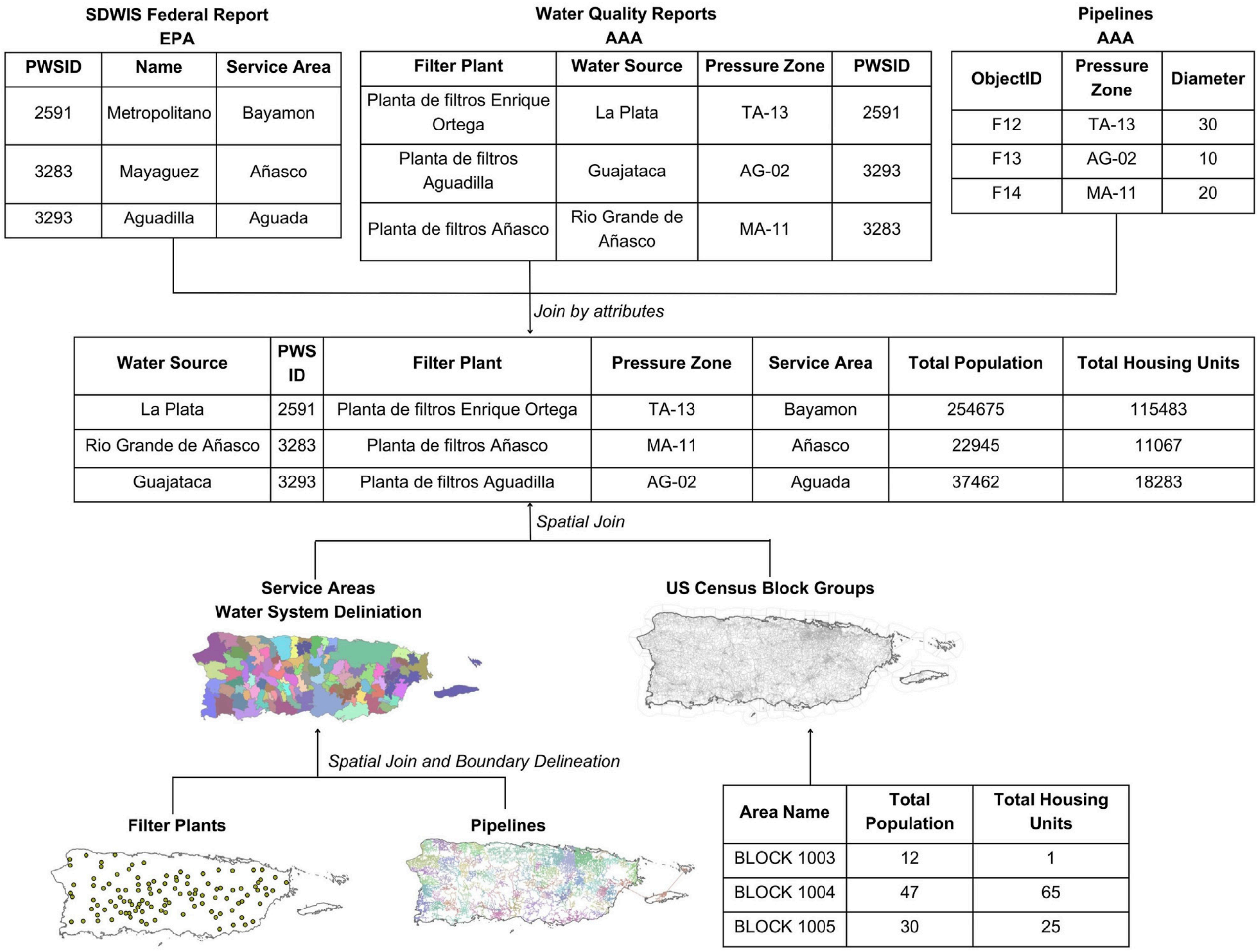

FIGURE 3
Summary of steps followed and the data used to estimate sediment retention ecosystem service demand by users of the reservoirs and water systems of the PR Aqueduct and Sewer Authority (PRASA).

was Guineo. These values correspond to the relative size of these watersheds, as La Plata is among the largest in area and Guineo among the smallest (Table 1). Corrected by watershed size, the mean avoided export was 78,617 tons/km^2. The watershed with the highest per area avoided export value was Luchetti with 154,148 tons/km^2, followed by the *RAN* watershed with 149,336 tons/km^2. The lowest per area avoided export was observed in Cidra, with 13,859 tons/km^2, followed by Guajataca, with 14,010 tons/km^2. The total avoided costs due to the avoided sediment exports ranged from $144,253 to $39,387,024, with an average $4,887,743 avoided costs per year.

According to our SEN estimates, the service demand (households connected) to each reservoir ranged from 1,365 to 250,775 households, with an average of 53,297 households per year (Table 2). Our estimates of the service demand (i.e., household users) were compared against the published values by PRASA of the estimated clients served by their reservoirs (Table 2), and there was a positive correlation of the values (R^2 = 0.56). While the number of households served on average by each reservoir was nearly identical (PRASA = 54,935, SEN = 53,407), the values were not comparable for some reservoirs, suggesting a discrepancy that we further address in our Discussion section. The largest discrepancy was found with the Cidra reservoir, which according to our SEN analysis is connected to 170,873 households, while the PRASA estimates that it serves 14,537 households. We speculate that PRASA estimates were corrected by the relative proportion of water extracted from this reservoir to each of these areas under normal conditions, while our study focused mainly on the number of households connected to the reservoir's network.

In terms of water demand, we estimated that a total of 307.36 Mm^3 of water is consumed annually from all the reservoirs under study, and an average of 20.33 Mm^3 per reservoir per year. We validated these values using existing data on actual water withdrawals from the Island. According to Molina-Rivera and Irizarry-Ortiz, (2021), water deliveries for 2020 were 1.48 Mm^3/day or 540 Mm^3 per year. Considering that surface water accounts for ~89% of water deliveries (Molina et al., 2019) and reservoirs account for ~70% of surface water withdrawals (Ortiz-Zayas et al., 2004; Quiñones, 2022), then the total annual water demand is approximately 336 Mm^3/year, which is similar to our estimate of 307.36 Mm^3/yr. The specific values of water demand per reservoir and how that compares to the current capacity for each of the reservoirs are shown in Table 2.

TABLE 2 Sediment retention demand, quantified as the number of people connected to the reservoir (SEN estimates) and characterized by the water systems being served and the reservoir current capacity.

Reservoirs	Capacity (Mm^3)	SEN-estimated households served	PRASA-estimated households served	Household water demand (Mm^3/yr)	Service areas
Carite	10.03	30,882	15,431	5.71	Guayama Urbano; Farallon
Cerrillos	36.84	55,727	51,430	19.03	Ponce Urbano
Cidra	5.43	170,873	14,537	5.38	Metropolitano, Cidra Urbano
Coamo	n/a	34,725	n/a	12.85	Coamo Urbano
Dos Bocas	13.42	27,266	n/a	10.09	Superacueducto, Corozal Urbano
Fajardo	5.47	25,864	31,514	11.66	Fajardo Ceiba
Garzas	4.83	10,505	n/a	3.89	Penuelas, Garzas
Guajataca	40.68	66,315	63,218	23.39	Isabela, Quebradillas Urbano, Lares Urbano, Aguadilla, Lago Guajataca
Guineo	1.79	4,849	n/a	1.79	Aceitunas
La Plata	29.36	151,621	130,828	48.41	Metropolitano, Airbonito La Plata, Cayey Urbano, Comerio Urbano
Loco	0.36	20,011	n/a	7.40	Lajas
Loiza^	13.15	250,775	179,387	66.37	Metropolitano, San Lorenzo Urbano
Luchetti	8.96	20,011	n/a	7.40	Lajas
Matrullas	2.92	1,365	n/a	0.51	Matrulla
Patillas	12.98	37,947	14,313	5.30	Guayama Urbano; Patillas Urbano
Portuguez	11.04	1,406	n/a	0.52	Guaraguao, Tibes
Prieto	0.002	25,683	n/a	9.50	Indiera Alta, Duey, Yauco
Rio Blanco	4.68	17,717	29,391	10.87	Rio Blanco Vieques Culebra
Retencion Acueducto Norte	n/a	110,624	n/a	40.93	Super Acueductropolitano, Barceloneta Urbano, Vega Baja Urbano, Tierra Nueva Rabanos, Manati East, Maguayo, Dorado Urbano
Toa Vaca	61.92	85,902	19,304	7.14	Ponce Urbano, Coto Laurel, Regional Villalba
Valenciano	12.75	17,979	n/a	6.65	Juncos Ceiba Sur
Vivi	n/a	6,913	n/a	2.56	Utuado Urbano, La Pica
Max	61.92	250,775	179,387	66.37	—
Min	0.002	1,365	14,313	5.30	—
Mean	14.56	53,407	54,935	20.33	—
Sum	353.09	1,174,960	549,353	307.36	—

*Sources for capacity: https://www.csagroup.com/markets/water/valenciano-dam-reservoir/; http://www.recursosaguapuertorico.com/embalses-principales.html. n/a means not applicable, information was not available. ̂Loiza reservoir is also called Carraizo. Estimates from PRASA and our SEN correlate positively (R^2 = 0.56)

The percent of natural areas in the watersheds of the studied reservoirs ranged from 50% to 98%, with an average of 82%. The percent protection ranged from 0% to 70%, with an average of 17%. The edge density ranged from 12 to 87 m/ha, with an average of 53 m/ha. The number of patches ranged from 18 to 19,082, with an average of 1,507 patches per watershed area. The patch density ranged from 0 to 5 patches per 100 ha, with an average of two patches per 100 ha.

The watersheds with higher than average avoided exports (service supply, Table 1; Figure 4) in order of value are Dos Bocas, La Plata, Loiza, Luchetti, and Toa Vaca. While all of these watersheds have a high percentage of natural areas (64%–86%), all have relatively low percentage of areas under the legal conservation status (0%–6.6%) (Table 2). Out of these, Toa Vaca had the highest fragmentation (ED = 87.31 m/ha, PD = 4.19). Loiza, La Plata, and Toa Vaca also rank as higher than average in terms of service demand (Table 2; Figure 4).

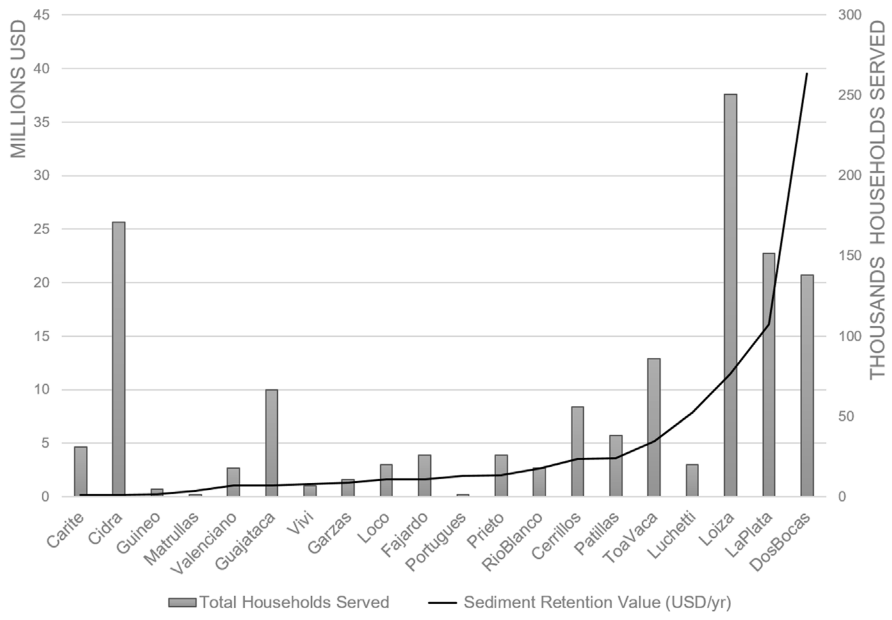

FIGURE 4
Supply vs. demand of sediment retention services. For the reservoir *Dos Bocas*, we used the estimates of population demand for *Retencion Acueducto Norte* and *Dos Bocas* combined (Table 2), as the latter drains and contributes water to the former.

The watersheds with higher than average service demand according to our SEN analysis (in order of demand) are Loiza, Cidra, La Plata, RAN, Toa Vaca, Guajataca, and Cerrillos. Out of these, Cidra and Guajataca had below average service supply in total and corrected by area (Table 1; Figure 4). Cidra stands out as having the lowest natural area (50%), low conservation status (0%, Table 3), and relatively high fragmentation (ED = 60.4, PD = 4.08) (Table 3). Loiza and La Plata have high total service supply and demand (Figure 4), but when correcting by area, they both have a lower than average supply (Table 1). Moreover, the percentage of natural areas under legal conservation status is low for these watersheds (2.79% and 4.15%, respectively, Table 3; Figure 5).

Dos Bocas can be considered to be having a high service supply (in total and corrected by area) and also a high demand if we take into account its position upstream from the *RAN* watershed. These watersheds would benefit from having been more formally protected from future development and land use change, as Dos Bocas has only 6.62% of its watershed under legal conservation status (1.48% for *RAN*). Toa Vaca also has a high service supply and relatively high demand, but high vulnerability, as its natural areas are among the most fragmented relative to other watersheds evaluated (ED = 87.31, PD = 4.19).

The Cidra and Guajataca reservoirs should be considered to be supply and demand mismatched because they are in high demand with lower than average supply of sediment retention service. These watersheds have natural areas of 50% and 67% (respectively), relatively high fragmentation (ED = 60.40 and 70.65, respectively), and low protection status (0%; 4%). These watersheds can be considered for restoration purposes to enhance their service delivery to the beneficiary populations.

Our SEN map results are shown in Figure 6 for a selected number of illustrative service areas and watershed areas. These maps illustrate how disparate locations across the island are connected to the network of natural stream features, and pipelines, and how landscape conservation in the watershed area of distant reservoirs benefits populations outside of these landscape units. These island-wide connections exist for other reservoirs and service areas as well, and Table 2 lists these linkages. Detailed maps for additional locations are available upon request, but were not included for the sake of brevity.

4 Discussion

4.1 Supply and demand analysis

The watersheds that supply water for consumption in PR have a relatively high percentage of natural areas, but most have little legal conservation and protection, making them vulnerable to development and land use change in the future. By estimating the avoided costs of sediment removal provided by these natural areas, and the number and location of people who are benefitted, we can develop conservation strategies for safeguarding this resource for future generations of the Island such as payment for ecosystem service schemes and targeted conservation easement programs that account for landscape prioritization by means of ES valuation.

Our estimates suggest that individually, the watersheds draining to reservoirs contribute an estimated \$4.9 million dollars per year in avoided costs. Sude et al., 2011 followed a similar approach to study sediment retention services for the Ertan Reservoir in Yalong River, China (101 km^2), and estimated 785.8×10^8 yuan of avoided costs in 1 year (year 2005), which amounts to a much larger value in USD than our estimates. On the other hand, another study in the Uma-Oya watershed in Sri Lanka (765 km^2) estimated the avoided costs of

TABLE 3 Vulnerability assessment of sediment retention service, quantified as the percentage of protection, and level of fragmentation of the vegetation in reservoirs' watershed areas.

Reservoirs	Vegetation protection		Vegetation fragmentation		
	% Vegetation	% Protected	Edge density (m/ha)	Number of patches	Patch density (#/100ha)
Carite	85.51	26.61	42.89	118	0.92
Cerrillos	90.82	10.05	45.62	367	0.78
Cidra	50.09	0.07	60.40	362	4.08
Dos Bocas	86.01	6.62	59.58	5102	1.25
Fajardo	90.94	42.80	32.08	275	1.89
Garzas	85.95	35.26	41.17	85	0.64
Guajataca	67.07	4.50	70.65	1304	4.60
Guineo	94.01	54.48	25.01	18	0.49
La Plata	72.63	4.15	73.63	7839	3.55
Loco*	92.08	44.75	56.19	254	2.57
Loiza	64.32	2.79	60.35	9082	3.67
Luchetti*	85.84	2.08	64.12	644	2.03
Matrullas*	84.63	23.64	40.12	104	1.38
Patillas	89.64	18.03	37.16	319	0.89
Portuguez	89.94	0.00	57.61	336	0.92
Prieto	90.58	14.15	45.49	149	0.72
Rio Blanco	97.97	69.88	12.05	55	0.23
RAN	64.63	1.48	45.51	586	5.34
Toa Vaca	84.74	0.00	87.31	1386	4.19
Valenciano*	55.27	0.00	64.32	728	3.99
Vivi	90.94	2.51	67.14	204	1.38
Max	98	70	87	9,082	5
Min	50	0	12	18	0
Mean	82	17	52	1,396	2

$34,215 USD annually, which is much lower than our estimates. These comparisons highlight that value estimates can vary depending on the parameters used and the assumptions. Here, we assumed that the reservoirs would be dredged in the event that the reservoir's capacity became compromised, and we also made assumptions regarding the discount rate of these avoided costs and the dredging costs themselves. Therefore, the actual avoided costs are meant here to provide a relative estimate, with these criteria in mind.

Despite these caveats, we can compare our avoided cost estimates to the recent Loiza (also known as Carraizo) reservoir dredging project in PR for further validation. In 2022, the project allocated an initial $88.7 million for dredging, after the reservoir had already been dredged in the year 1997 (FEMA, 2022a). This amounts to at least ~$3.5 million/yr of cost accrued in 25 years, which is not too far from our estimates, especially when considering that the planned dredging volume 2 Mm^3 (2.6 million cubic yards) is lower than that of the actual sedimentation that occurred in this time period (4.39 Mm^3, FEMA, 2022b). Moreover, the measure of avoided sediment removal costs from dredging does not account for other co-benefits of sediment retention services, including recreational uses, fisheries, and biodiversity conservation. In addition, previous studies have calculated other ESs provided by the same natural areas, such as nutrient retention, carbon sequestration, and flood risk reduction, which have been documented as valued by residents in PR (Smith et al., 2017), and to contribute co-benefits beyond monetary valuation, such as increases in human wellbeing (Yee, 2020).

When extrapolating the number of households connected to reservoirs into the estimates of water demand, we observe that the level of annual water withdrawals (i.e., 307.36 Mm^3) is very close in value to the total capacity of the reservoirs being withdrawn from (353.09 Mm^3). On average, the annual demand for water from individual reservoirs (20.33 Mm^3) exceeds the existing capacity

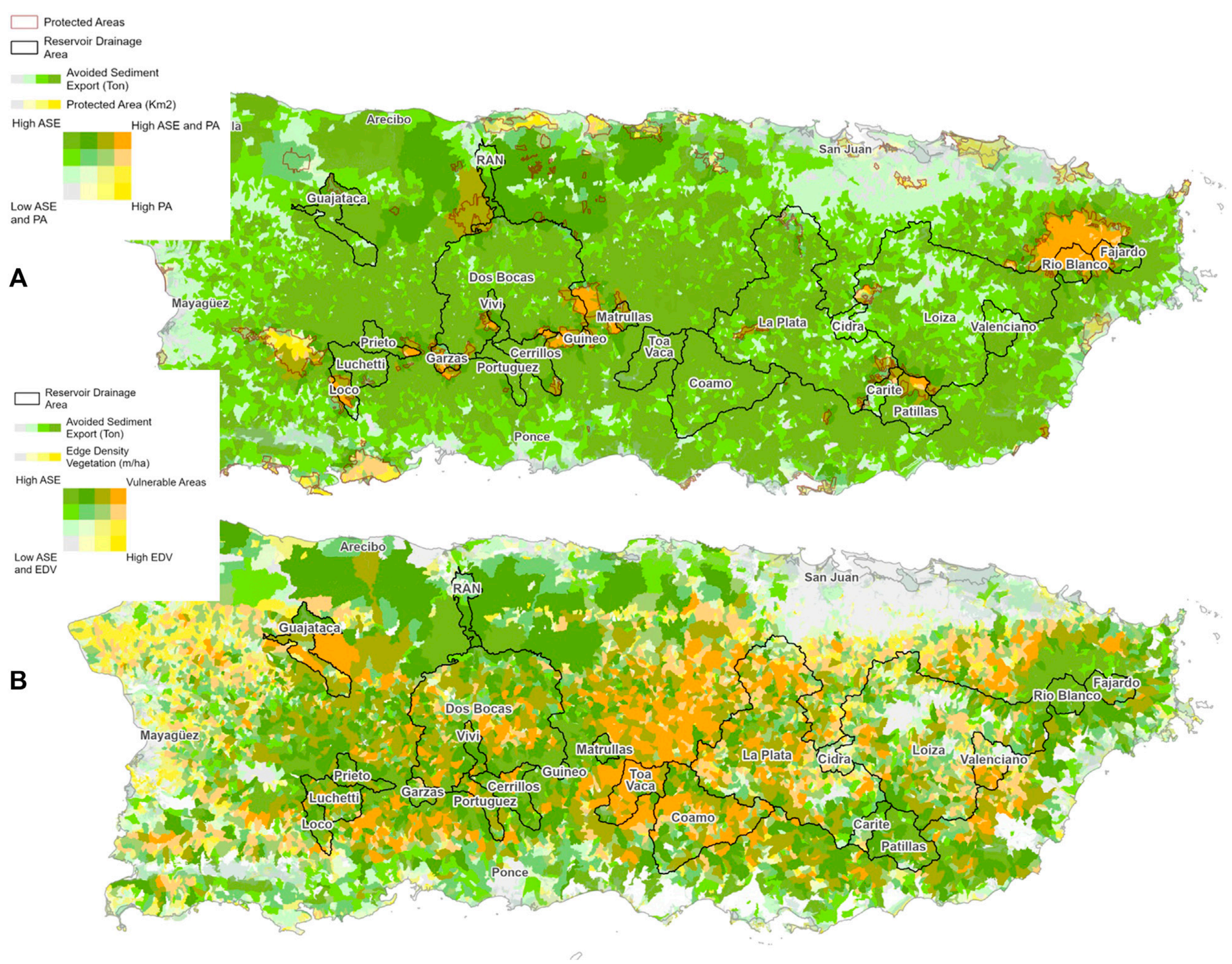

FIGURE 5
Avoided sediment export at the micro-catchment scale for the reservoirs under study. Panel **(A)** depicts avoided sediment export in relation to the percent of protected areas. Panel **(B)** depicts avoided sediment export in relation to edge density, an indicator of fragmentation. RAN, *Retencion Acueducto Norte*.

(14.56 Mm^3). While these estimates should be considered carefully, with all the limitations of our study in mind, these estimates support a need for developing proactive strategies to prevent further capacity loss, an imperative that may become more crucial in the future, if there are changes in the precipitation regime (droughts and hurricanes) that exacerbate the vulnerability of reservoirs in PR.

4.2 Vulnerability analysis

Our study characterized the level of legal protection of sediment retention services across the Island. The most important reservoirs in terms of service demand according to our study, Loiza, La Plata, and Dos Bocas, have a high percentage of natural areas in their watersheds which provide high levels of sediment retention. However, they have a low percentage of protected areas, which makes their watersheds vulnerable to future development, which may disrupt the systems of natural functions underpinning the ecosystem service provision. This is relevant in terms of relating ecosystem service flows to strategic watershed conservation initiatives, which have been highlighted as crucially essential for post-hurricane resilience on the Island (Preston et al., 2020). It is also important in terms of relating issues of water provision to land use regulation and planning policy. For example, this analysis would inform PRASA water users about the potential impact of changes to land use classifications under the Puerto Rico Land Use Plan and Joint Permitting Regulation (Puerto Rico Planning Board, 2022) to the reservoirs that provide water for their consumption.

A reservoir system that seems to be vulnerable according to our study is Cidra, which serves a large population, but has a low percentage of natural area and higher than average fragmentation. Cidra's high demand estimates can be attributed to its connection to the Metropolitano system, for which it may contribute a small proportion of the total amount of water. However, the fact that it is connected to a high population area and that it also connects to different service areas that rely on it solely (Cidra Urbano) highlight the potential need for its management. Previous sedimentation surveys on the Cidra reservoir suggest

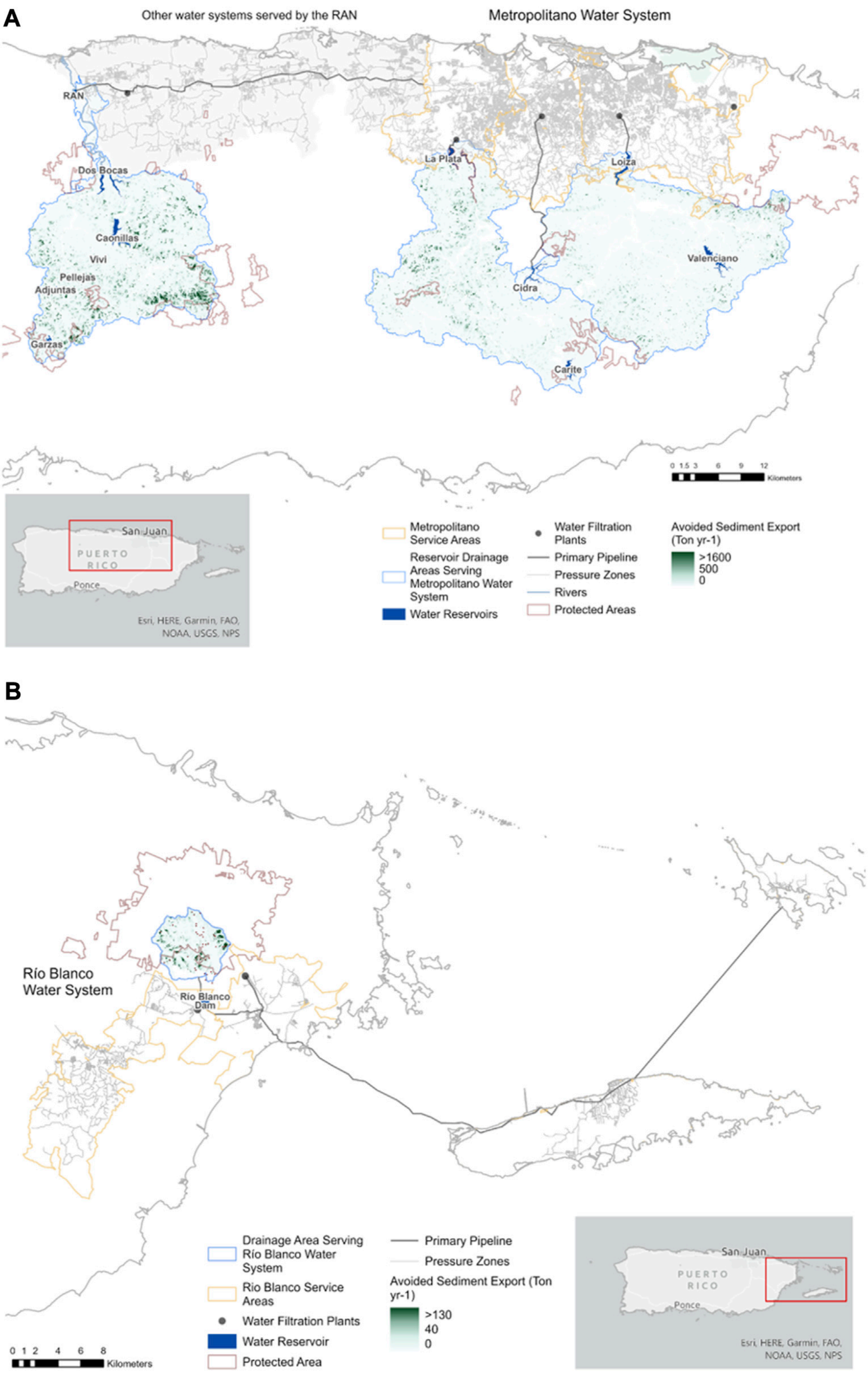

FIGURE 6
Maps depicting examples of our SEN results for the supply and demand of sediment retention services of reservoirs in PR. Panel **(A)** is analogous to panel **(A)** in Figure 1, and depicts the service area of *Metropolitano*, which corresponds to the San Juan metropolitan area, and all the reservoirs and watershed areas connected to it. Panel **(B)** is analogous to panel **(B)** in Figure 1 and depicts the watershed area of *Rio Blanco* reservoir and its linkages to multiple service areas including the islands of Vieques and Culebra, and also the municipalities of PR. RAN refers to *Retencion Acueducto Norte*. Other service areas and reservoir linkages are shown in Table 2.

that there is no immediate concern for capacity loss for this reservoir due to sedimentation in the near future (Soler-Lopez, 2010). However, sedimentation has been shown to affect the reservoir's operational capacity, as water intake structures and sediment discharging structures (sluice gates) have been buried by 8–9 feet of sediment (Ortiz-Zayas et al., 2004). Another highly fragmented watershed area is that of Toa Vaca, a reservoir with high sES demand and supply, but which would benefit from conservation and restoration initiatives, especially given its current capacity, which is high and suggests its potential to serve an even larger population in the future. While this study showed high ES supply, the Toa Vaca drainage area also stands out as having one of the highest per area sediment export rates of all major reservoirs according to previous studies, supporting the need for watershed planning to avoid further increasing erosion and sediment export rates in the future (Ortiz-Zayas et al., 2004).

4.3 Application of findings

Our findings may help inform the development of payment for ecosystem service schemes that use these dollar value estimates as a guideline. For example, a municipality in PR interested in community-based conservation efforts could designate annual fees to water consumers for the protection of the service provisioning units of their primary reservoirs. For an average reservoir with 54,297 households and $4.9 million dollars in sediment retention service, this would imply a $90 annual fee or approximately $7 per month per household, which could then be used in coordination with existing NGOs and organizations on the Island to develop strategic conservation programs (e.g., *Para La Naturaleza*, *Foundation for Puerto Rico*, *Centro para la Conservacion del Paisaje*, and *Protectores de Cuencas*). Here, we must note that in Puerto Rico, utility rates are much higher than in the US (United States Environmental Protection Agency, 2023) and the poverty level doubles that of the poorest state (ACS, 2021). Adding even a small fee to an already exceedingly expensive utility system for the PR citizens may not be the first approach to consider. Alternatively, already existing programs and fees may be used toward these goals. For example, PRASA already charges residents two relevant fees: 1) environmental and regulatory compliance charge (CCAR) and 2) a water sustainability charge (PRASA, 2022). Perhaps the strategic use of these already collected funds could be considered for ES management, which is an important aspect of water sustainability in PR.

The selection of the best places to focus for conservation easements and other protection strategies could then be informed by our fine-scale map of micro-catchment (Figure 5) within each watershed area, which provides information regarding total sediment retained and current level of protection and fragmentation. The actual cost of acquiring and conserving properties for sediment retention services has not been factored in this study and could be the focus of future studies that complete a more expansive cost–benefit analysis of payment for the ecosystem service program on the Island. These analyses may also include other co-benefits such as flood control, recreational opportunities, and biodiversity conservation, all of which would add to the value of acquiring land for conservation.

Our study is the first one to provide a clear characterization of the supply and demand of sediment retention ES flows for the island of Puerto Rico. By knowing which landscapes contribute to the water quality of which citizens, we can develop more targeted conservation strategies and community-led efforts for ES management. For example, we showed a link between the protected areas of the Luquillo National Forest, the only tropical federal forest of the Nation, and the water quality of the islands of Vieques and Culebra, which are the end users of the Rio Blanco reservoir, and direct beneficiaries of the conservation of these natural areas (Figure 6). We also showed how the residents of the San Juan metropolitan area benefit not only from the nearby La Plata and Loiza reservoir watersheds but also from the more distant Dos Bocas, which is directly linked to the water supply of the *Retencion Acueducto Norte*. This information provides the citizens of PR with a better understanding of the value of vegetation conservation and management across the Island, and at fine scales, in order to see which landscapes and micro-catchments to target in order to protect and enhance sediment retention. Table 2 shows other linkages across the Island.

Our study also presents a replicable process to apply for operationalizing the characterization of supply and demand flows of ES. Our suggested SEN process can be applied or customized as needed for other applications. This could include the addition of relational ties to plans and laws at different scales for governance analysis, more detailed incorporation of natural functions and landscape data for modeling, or additional consumer information for future value estimations based on service–consumer linkages. The context of water quality service flows presents an opportunity to create concrete measurements of socio-ecological linkages, as stream networks and pipelines connect landscapes to end users, and these data are widely available, at least in the United States, from utilities, and via Safe Drinking Water Act and Clean Water Act (SDWA and CWA) reporting databases. PR was an ideal case study for the application of the suggested approach because the Island is the single source of ES, and PRASA serves most of the population as a Commonwealth wide utility. While the approach could be used in other locations, we should note that it would require acquiring the system service data for the lines potentially from several utilities and jurisdictions. SDWA and CWA data, for example, associate reservoirs with locations of demand, but these are jurisdictional attributes, without specific spatial data on service areas and service lines. Additional studies are needed to determine how feasible it is to replicate this process in other locations and what are the data gaps and challenges that need to be overcome to do so. Additional limitations of our study are discussed as follows.

4.4 Study limitations

Our study had several limitations. The InVEST SR model is not meant to provide a comprehensive sediment budget for reservoirs, as the avoided sediment export values only account for overland erosion and does not include estimates for gully erosion, channel erosion, or landslides (Natural Capital Project, 2022). In Puerto Rico, landslides may constitute the majority of the sedimentation source for surface waters (Larsen, 2012); therefore, our estimates only cover a portion of the sedimentation risk in surface waters on the island. Nevertheless, the processes that lead to avoided sediment export by vegetation also contribute to reducing landslide risk. For example, a study by Larsen (2012) compared sediment exports and sources of four watersheds in PR and found a higher rate of landslides in urbanized vs. forested watersheds. In addition, the process of fragmentation, which we suggest here that it can affect the provision of overland sediment retention, can also increase the risk for other forms of erosion. For example, it has been suggested that road construction, which fragments forested areas, is a leading cause of landslide occurrence in PR (Larsen and Torres-Sanchez, 1992; Hughes and Shulz, 2020). Therefore, the mapping and prioritization data presented here can be beneficial for the management of erosion issues in the island as a whole, and not just from overland erosion. Previous studies have also conducted similar mapping characterizations for the risk of landslides through the island (Hughes and Schulz, 2020). Using this information, we developed a supplementary map showing how landslide risk relates to our estimates of avoided exports from overland erosion (Supplementary Material S4).

While the network of the reservoir to filter plant to pipeline allows a rough estimation of the number of end users for each reservoir's water, the fact that pipelines receive water from multiple sources makes it more complicated to determine the relative importance of each reservoir source that contributes to the same distribution system. Therefore, our estimates of connected households could be further refined in future studies to include relative weights accounting for the proportion of water provided by each reservoir to each system. Here, we note that our estimates of consumers linked to the selected watershed areas do not fully match the estimates of clients served published by PRASA in their website. We were not able to find the methods used by PRASA to provide their estimates, but it is possible that their methods account for the relative importance of each reservoir to the end users connected, as well as potential losses during the distribution process. Despite these discrepancies, the relative importance to users of the reservoirs studied correlated with the PRASA numbers, and therefore our analysis still provides a good estimate of relative differences in service demand, even if the absolute number of users required further validation.

Our assessment of the vulnerability of services is based on the assumption that the fragmentation of natural areas would likely cause a reduction in the ES supply and that natural areas under any form of the legal conservation status should be better protected against development. These assumptions need to be tested in greater detail in the future.

Lastly, our model estimates are based on the best available publicly accessible datasets. Some of these data (e.g., 2010 PR CCAP land use and land cover) would need to be updated once new information is available to better reflect the current conditions on the island. However, since our methods have been documented in detail and are based on open source software and data, we believe our results can be replicated fully to update them as needed and help inform management of reservoir sedimentation.

5 Conclusion

Water consumers in Puerto Rico benefit from sediment retention services from natural landscapes across the Island. These services can amount to millions of dollars annually if we consider the potential costs of reservoir dredging. Our study provides a valuation of these services and a characterization of the service flows from watershed areas to reservoirs to end users, which show how people in one side of the island benefit from distant natural landscapes in their everyday lives. This characterization is useful for raising awareness about the importance of ecosystem service conservation and also a framework for future studies to evaluate socio-ecological networks of water quality ecosystem service flows. Despite the value of sediment retention services by natural landscapes in Puerto Rico, these landscapes are vulnerable due to the low level of legal conservation, fragmentation, and potential changes to zoning regulations that have been proposed in PR. The information we provide here can assist decision makers and communities in prioritizing areas for conservation and management to address these vulnerabilities in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials; further inquiries can be directed to the corresponding author.

Author contributions

Conception and design of the work (RD and TD); acquisition, curation, and analysis of data (MV, VM, RD, and TD); design and formatting of figures and tables (MV, RD, and TD); drafting of the manuscript (RD, TD, MV, and VM); revising the manuscript critically for important intellectual content (RD, TD, MV, and VM). All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1214037/full#supplementary-material

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Citizen science benefits coral reefs and community members alike

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The field of coral gardening and active restoration has expanded rapidly over the past 2 decades in response to the rapid, global decline of coral reefs. Even with this expansion, the long-term success of coral restoration and ecosystem recovery will still depend on social action to mitigate the local and global stressors plaguing reefs. Rescue a Reef (RAR), a citizen science program, was designed to engage community members and catalyze action through hands-on, experiential opportunities as coral gardeners and restoration practitioners alongside trained scientists. While community-based coral restoration programs can be a powerful platform for education and increase project success, few programs utilize citizen science and even fewer measure and evaluate the long-term impacts of these activities. Here, we describe the benefits of citizen science for coral conservation identified through a mixed methods longitudinal evaluation of RAR after 8 years of citizen science programming. A survey was distributed to all program participants and responses were compared to historical pre-post survey responses of citizen scientists as well as to a control group. We found that despite the passing of time, citizen scientists largely retained their knowledge levels on coral reef-related topics and were significantly more knowledgeable on the topics than a control group. Additionally, RAR successfully developed a strong sense of community, coral stewardship, and program support among its participants. Most importantly, citizen science has the potential to act as a vehicle for positive social change with the majority of participants reporting changes in perceptions (70.5%) and behavior (60.1%) because of their participation in RAR. Thus, the untapped potential of citizen science as a tool for coral reef conservation, restoration, and stewardship must be realized. Furthermore, citizen science projects must embed evaluation in their activities to gather information and evidence on the effectiveness of their activities as well as potential areas for improvement.

KEYWORDS

coral reef, coral restoration, citizen science, education, social change, coral conservation, community engagement, community psychology

1 Introduction

Coral reefs are one of the most important ecosystems on our planet. They protect our coastlines, acting as a natural barrier that can mitigate erosion, storm surge, and hurricanes (Ferrario et al., 2014; Beck et al., 2018; Storlazzi et al., 2019). They support biodiversity, serving as refuge, feeding, and/or mating grounds to an estimated 30 percent of all marine species (Fisher et al., 2015). They sustain communities, providing a source of protein for over one billion individuals (Whittingham et al., 2003). Coral reefs also drive economies, supporting important sectors like tourism, recreation, research, and fisheries with the United States' reefs alone estimated to provide $3.6 billion in goods and services annually (Brander and van Breukering, 2013).

However, coral reefs have experienced dramatic declines in the past 40 years due to both local and global stressors (Bruno and Selig, 2007; De'Ath et al., 2012; Jackson et al., 2014; Lester et al., 2020). Globally, rising ocean temperatures due to anthropogenic greenhouse gas emissions are causing mass coral bleaching events and die-offs with increasing frequency and severity (Manzello, 2015; Hughes et al., 2018). Additionally, these excess emissions are causing increases in ocean acidity, making it more difficult for corals to grow and reproduce (Muehllehner et al., 2016; Richmond et al., 2018; Morris et al., 2022). Locally, coral reefs are being impacted by a combination of pollution, coastal development, overfishing, and disease (Precht et al., 2016; Cunning et al., 2019; Lapointe et al., 2019; Hayes et al., 2022). To address these declines, the field of coral gardening and reef restoration has expanded rapidly in the past 2 decades. There are now hundreds of coral restoration programs that have restored thousands of square meters of degraded reef habitat around the world (Boström-Einarsson et al., 2020).

The field of active coral reef restoration is constantly improving as scientists develop and implement innovative coral restoration tools, techniques, and strategies (Goergen et al., 2020). Recent advances have led to: 1) increased outplanting efficiency and effectiveness (Schopmeyer et al., 2017; Bayraktarov et al., 2020; Unsworth et al., 2021), 2) new species being integrated into gardening and active restoration (Forsman et al., 2015; Page et al., 2018; Rivas et al., 2021), 3) increased success with *in-* and *ex-situ* sexual reproduction as a tool to establish gene banks, bolster nursery stocks, and increase genetic diversity of restored populations (Petersen et al., 2006; Hagedorn et al., 2021; Henry et al., 2021; O'Neil et al., 2021), and 4) the identification of more resistant and resilient coral populations, species, and genotypes as well as methods to "harden" individuals to stressors like high light intensity and water temperatures for use in reef restoration (Silverstein et al., 2012; Cunning et al., 2021; Kaufman et al., 2021; DeMerlis et al., 2022). Coral restoration has been shown to significantly increase coral cover and structural complexity of reef restoration sites compared to unrestored sites (Hein et al., 2020). Staghorn coral has been shown to significantly enhance the wave-reducing capacity of a reef for coastal protection benefits (Ghiasian et al., 2021). Restoration has also been shown to significantly increase fish abundance and species richness post-outplanting (Opel et al., 2017). Despite these advancements, the long-term success of coral restoration and reef recovery will depend on social action to mitigate local and global stressors (Hoegh-Guldberg et al., 2019; Boström-Einarsson et al., 2020; Ferse et al., 2021; Kleypas et al., 2021; Suggett et al., 2023). While scientists have been calling for action on these stressors for decades, traditional methods of informing and educating individuals has not translated to meaningful social change (Moser, 2010).

Therefore, in 2015, we developed Rescue a Reef (RAR), a citizen science coral restoration program designed to act as a vehicle for public engagement, education, and social action. Led by coral researchers from the University of Miami, the RAR program hosts field expeditions that provide an educational, experiential opportunity for recreational SCUBA divers and snorkelers to participate directly in coral gardening and reef restoration efforts. Members of the public ("citizen scientists") work alongside coral scientists helping to maintain nursery structures, collect coral fragments, and outplant colonies to local reef restoration sites while learning about the importance and impact of the activities.

Citizen science is as it sounds: everyday citizens contributing to science. Public participants or volunteers work in collaboration with trained scientists to carry out research, data collection, and/or analysis for a scientific project (Bhattacharjee, 2005; Bonney et al., 2009). Citizen science projects are designed to be symbiotic, providing benefits to both scientists and citizens. Citizen science allows the scientists to advance their projects beyond their own capabilities, and it helps engage the public in science to promote literacy, knowledge, and stewardship (Brossard et al., 2005; Jordan et al., 2011; Crall et al., 2013). Citizen science projects are an ideal fit for scientific endeavors with important environmental and social implications, like coral conservation, because they can directly engage local stakeholders and help foster a sense of identity and connection with the project community over time (Dickinson et al., 2012; Jackson et al., 2015; Bela et al., 2016). This sense of community is critical as social change requires the empowerment of individuals and a shared mission that includes the voices of those impacted (Gruber and Trickett, 1987; Kloos et al., 2012; Bond et al., 2016; Dosemagen and Parker, 2019). Citizens in communities with community-based monitoring tend to be more engaged in local issues, community development, and civic duties (Conrad and Hilchey, 2011). The social impacts of citizen science are not exclusive to the citizens either. A review by Bela et al. (2016) of 14 case studies of citizen science initiatives found that more interactive, hands-on projects were able to facilitate a mutual exchange of knowledge between both the citizens and the scientists. This same review found that citizen science activities also allow scientists to acquire and improve their collaborations skills, a critical development with the growing need for interdisciplinary research to solve today's complex environmental issues.

Coral restoration has the potential to be a powerful platform for education, stewardship, and conservation strategies (Hein et al., 2019). Community-based participation in coral restoration can promote knowledge gains and strengthen decision-making of participants, and increase the success of overall project activities (Hernández-Delgado et al., 2014; Goergen et al., 2020; Suggett et al., 2023). A review by Hein et al. (2017) of 83 published studies on coral restoration identified six primary objectives, one of which was to "promote coral reef conservation stewardship" as practitioners recognized the need for community education and empowerment. After 2 years of programming, an evaluation of RAR citizen science activities showed that there was no significant difference in the survivorship of corals outplanted by participants compared to corals outplanted by experienced scientists (Hesley et al., 2017). Additionally, retrospective pre-post survey results showed that participants reported a significant increase in coral reef ecology and restoration knowledge following participation in an expedition. However, citizen science practitioners recognize that additional resources must be put into data-driven, measurable projects to assess potential long-term impacts of the activities (Brossard et al., 2005; Bonney et al., 2009; Posavac, 2011; Crall et al., 2013; Bela et al., 2016).

That is what this program evaluation sought out to do. As a community-based program, we have a responsibility to ourselves and the communities we serve to formally evaluate our activities and ensure we are reaching desired outcomes and realizing impact (Bela et al., 2016). Community-based program evaluation is a critical process that involves assessing the effectiveness, efficiency, and impact of the activities that the program is designed to address (O'Leary, 2005; Frechtling, 2007; Gill, 2010; Posavac, 2011). The RAR program was designed to raise awareness, develop a sense of community, and foster coral stewardship among its participants. After 8 years of citizen science activities, we launched a mixed-methods longitudinal evaluation using quantitative and qualitative data to better understand RAR's progress and the potential long-term impacts and benefits of the program.

To guide our evaluation, we used our RAR program's Logic Model (Supplementary Figure S1) as a framework. A Logic Model is a tool that describes an organization's theory of change underlying an intervention and outlines a project through four basic components: 1) inputs, or the resources that are brought to the project, 2) activities, or the actions that are undertaken by the project to bring about desired outcomes, 3) outputs, or the immediate results of an action, and 4) outcomes, or the changes that occur showing progress toward achieving the ultimate objectives and goals of the program (Frechtling, 2007). Logic Models can provide the scaffolding for a program evaluation by helping define and clarify what should be measured and when.

The RAR program's Logic Model helped establish the following guiding questions:

1) Have we fostered a sense of community and stewardship among participants?
2) Have knowledge levels changed over time?
3) Have perceptions and/or behaviors changed over time?
4) Was the evaluation process beneficial?

In 2017, an evaluation of the RAR program established that citizen science benefits coral reef restoration activities (Hesley et al., 2017). Despite this, few coral restoration projects integrate citizen science into their activities and even fewer evaluate the long-term benefits. With these things in mind, we launched another evaluation to understand the potential latent social impacts on individuals in relation to our RAR citizen science activities. Our priority was to self-reflect, assess, and adapt in hopes of improving our activities and communicating the lessons that we have learned. Here, we describe our RAR program's outcomes, effectiveness, and impact.

2 Materials and methods

To formally assess the potential educational and behavioral impacts of our citizen science program, a mixed methods longitudinal evaluation of RAR was carried out. This included a within-group evaluation (i.e., reviewing retrospective pre-post surveys of the RAR program participants immediately following an expedition and again 1+ years later) and a between-group evaluation (i.e., establishing a control group to act as a baseline for comparison). As a community-based program, RAR's participants are one of the most inexpensive, accessible, and accurate data sources available and were therefore a priority of the evaluation (Posavac, 2011). There are limitations to only evaluating within-group information (e.g., sampling bias, reactive measures) so this assessment was anonymous and included multiple measures (i.e., a control group, mixed methods) to improve the validity of the evaluation.

The longitudinal evaluation was completed using a survey instrument developed in alignment with the NOAA Coral Reef Restoration Monitoring Guide sociocultural performance metrics (Goergen et al., 2020) (Supplementary Figure S2). The survey instrument was designed using Qualtrics and distributed via email to every individual who had previously participated in an RAR citizen science coral restoration expedition. The survey link was also shared on RAR's social media platform in case past participants no longer used or monitored their email. The timing of survey distribution (August 2021) gave us a unique opportunity to evaluate the long-term impacts of the citizen science activities as around a year had passed since RAR last hosted an expedition due to the COVID-19 pandemic. Hereafter we therefore refer to this group of individuals as "latent-expedition" or simply "latent" citizen scientists because of the time that had passed and the potential for enduring impacts.

This new longitudinal evaluation survey instrument was structured to mirror the standard survey that is distributed to participants immediately after the completion of each RAR citizen science expedition. Rescue a Reef expeditions feature a 30-min educational lecture and tutorial as well as hands-on coral husbandry and reef restoration activities within Miami-Dade County, Florida as described by Hesley et al. (2017). The standard survey shared after these expeditions has a retrospective pre-post format and consists of questions to assess Likert scale knowledge levels for both before (pre-) and immediately after (post-) restoration expeditions. Historical survey responses collected from individuals following participation in an expeditions between 2015–2020 were used for analyses here when applicable. This group contained both "pre-expedition" and "post-expedition" data due to the nature of the retrospective pre-post survey instrument, despite this survey only being distributed to individuals after participation in an expedition.

To establish a "control" group and create baselines for comparison, the latent-expedition citizen science survey instrument was modified slightly and distributed to individuals who had never interacted with our RAR program before (Supplementary Figure S3). This survey instrument was distributed by Qualtrics to a stratified random sample of Florida residents 18 years of age or older. Both the latent group and control group surveys were distributed in August 2021. All groups were informed that the surveys were voluntary and anonymous, and were designed solely for the purpose of evaluating the potential impacts of our activities as well as areas for improvement. For these reasons, the University of Miami determined that this project evaluation did not constitute human subject research requiring IRB review.

2.1 Survey design

The surveys consisted of multiple choice, Likert scale, rank order, and open-ended questions, dependent on what was being assessed (Supplementary Figure S2, S3). In brief, the questionnaires were designed to capture information on 1) demographics, 2) knowledge levels (perceived and realized), 3) program support, and 4) reported changes in perceptions and/or behavior, to empirically evaluate the sociocultural impacts associated with coral restoration projects (Goergen et al., 2020).

The demographics portion of the survey captured age, residency, education, level of engagement with RAR, among other things. The second section assessed their perceived knowledge levels on coral reefs, threats they face, and tools available for conservation as well as their confidence in communicating these topics to others via Likert scale and rank order questions. The third section sought to evaluate overall program belongingness and support. The fourth section aimed to determine their realized knowledge levels on the aforementioned topics via open-ended questions which can create rich opportunities for discovery of new concepts (Gioia et al., 2013). The final section aimed to assess reported changes in respondents' perceptions of coral reefs and/or behavior changes resulting from interacting with RAR as well as suggestions for improving our program.

2.2 Survey analysis

For each data set we removed individuals who completed less than 70% of the survey questions. We also removed individuals who we confirmed used online searches to populate their open-ended question responses (i.e., "cheated"). For the latent-expedition survey, we removed 39 individuals who indicated that they had not participated in an RAR expedition, likely a result of misunderstanding the instructions, as we were specifically assessing the impact of those who participated in the citizen science activities. We also removed those whose first expedition took place within a year of the latent survey distribution as they are more comparable to the retrospective post-expedition group than the rest of the latent-expedition group. For the control survey, Qualtrics quality checked the data to filter out bots and duplicates, and flagged responses that appeared insincere due to quick survey completion time/rushed responses or responses not based on the question or topic at hand. We reviewed these flagged individuals and agreed with the Qualtrics consensus, deleting them in addition to a few other low-quality responses.

All statistical analyses were conducted in R Studio Version 1.3.959. Shapiro tests were used to determine if the Likert-scale self-reported knowledge levels on coral reef-related topics were normally distributed across groups, and all mean comparison analyses required nonparametric tests. We did not use single 3-way means comparisons to compare knowledge levels between the control, post-expedition, and latent-expedition groups, as the post- and latent-expedition groups are more related from being drawn from the same population of RAR citizen scientists. We instead used separate Mann-Whitney U tests to compare 1) control to pre-expedition, 2) control to post-expedition, 3) control to latent-expedition, and 4) post- to latent-expedition separately. Histograms were used to assess if the shape of the knowledge level distributions were similar enough between groups to allow for interpretation of results as [non]significant differences between mean ranks. Knowledge level distributions were only similar enough across groups for survey questions about reef status and reef threats to warrant the interpretation of results as significant differences in mean ranks. Due to the variable distributions of Likert knowledge levels of reef ecology and conservation tools, we interpret these significant differences as stochastic dominance. Changes between pre-expedition and post-expedition Likert-scale responses were not statistically analyzed as these were the primary focus of a past evaluation (Hesley et al., 2017).

We also used Mann-Whitney U tests to compare the Likert-scale confidence communicating about coral reefs, comfort contacting "key coral reef organizations" (control) or "Rescue a Reef" (latent-expedition), and likelihood of supporting "coral conservation" (control) or "Rescue a Reef" (latent-expedition) in additional ways between 1) latent and control groups and 2) total number of RAR trips, as Shapiro tests and visualizations indicated distributions were significantly different from normal. Total number of RAR expeditions were pooled into groups representing 1 or 2+ expeditions due to small sample sizes. Questions about comfort communicating, contacting, and supporting RAR in additional ways were not asked in the retrospective pre-post survey and therefore these analyses did not include the immediate post-expedition group. The distributions of the results were similar enough between total RAR trip groups for all three questions and were similar enough for communication confidence between latent and control surveys, to warrant interpretation of results as a significant difference between mean ranks. The other comparisons must be interpreted as stochastic dominance.

We used chi-square tests to explore the influence of survey group on the ranking of coral reef conservation activities between control and latent groups, but not the post-expedition group as this question was not asked in the retrospective pre-post survey. We first did a frequency analysis of the top ranked item between groups, excluding fisheries management as a solution due to low expected frequency. Then for addressing climate change, coral reef restoration, and managing land-based pollution, we compared the frequency of respondents who assigned these actions the highest rank of 1, *versus* any lower rank (2+), between control and latent groups.

For the open-ended question responses, a blended approach of inductive and deductive coding was used to ensure we both gave voice to the respondents and stayed attuned to existing theories, respectively (Gioia et al., 2013; Elliott, 2018; Skjott Linneberg and Korsgaard, 2019). Three cycles of qualitative analysis to translate the various responses into specific codes were completed. The first-order analysis is meant to adhere to the phrases or terms used by the respondents themselves and can produce anywhere from 10 to 100 first-order categories. The categories that emerged were then reviewed and distilled into a more manageable number of themes reflective of the literature for second-order analysis. Completing the second cycle of coding with the second-order themes helped solidify the final codes to be used for analysis. The third and final cycle of analysis determined the response code as well as the total number of coded responses provided by each individual. Each unique response was only included in the single, most relevant theme. The open-ended question themes, codes, and code acronyms can be viewed in Table 1.

Chi-square tests were used to determine if there were significant associations between survey groups and frequency of the coded responses provided for both the ecosystem services and largest issues facing coral reefs. These analyses were run separately between 1)

TABLE 1 Resultant codes and themes produced from coding of open-ended question survey responses to (A) "What are the largest issues facing coral reefs?", **(B)** "What ecosystem services to coral reefs provide?", and **(C)** "Can you please describe what behavior/action(s) have changed (because of your interaction(s) with Rescue a Reef)?".

Code category	Open-ended response themes
A	
Pollution (POL)	Pollution (not marine debris), water quality, nutrient levels
Climate change (CC)	Climate change, global warming, sea level rise, extreme weather events
Ocean warming (OW)	Increasing ocean temperatures, coral bleaching
Humans (HUM)	Human-induced impacts at a local scale–marine debris, coastal development, sunscreen, irresponsible boating
Ocean acidification (OA)	Ocean acidification, accelerated erosion
Disease (DIS)	Coral diseases
Overfishing (OF)	Destructive fishing practices, poor fisheries management
Lack of education (LOE)	Lack of education, awareness, and stewardship
Population scarcity (POP)	Low coral populations, habitat fragmentation
No response (NR)	Left question blank, "I do not know," unrelated/incorrect response
B	
Habitat (HOM)	Home, habitat, shelter for marine organisms
Coastal protection (PRO)	Coastal protection, defense, wave attenuation
Food webs (FF)	Supporting food webs, source of food for marine life
Biodiversity (BIO)	Hotspot for marine life, supporting ocean health/ecosystem function
Human food source (EAT)	Food source for local and global communities
Water quality (CLN)	Water filtration, water cleansing
Economic driver (DOL)	Economy, tourism, recreation, fisheries, jobs, intrinsic value
Nursery (NUR)	Breeding grounds and nursery for marine life
Oxygen (OXY)	Oxygen production
Medicine (MED)	Medicine, pharmaceuticals
Wrong (WR)	Unrelated or incorrect response
No response (NR)	Left question blank, "I do not know"
C	
Advocacy (COMM)	Increased advocacy, communication, and education of others
Eco-friendly choices (ECO)	Lowering carbon footprint, choosing more eco-friendly products conscientiousness about sustainability
Reduce/reuse/recycle (RRR)	Reducing materialistic consumption, avoiding single-use plastics recycling more
Reef-safe sunscreens (SUN)	Using sunscreens without chemicals that harm coral reefs
Volunteering (VOL)	Volunteering, citizen science, donating to environmental organizations
Responsible diving (DIVE)	Proper buoyancy, avoiding spreading sand, not touching the reef
Responsible fishing (FISH)	More sustainable recreational fishing, safer boating practices
No response listed (NRL)	Left question blank

control and post-expedition, 2) control and latent-expedition, and 3) post- and latent-expedition, rather than running 3-way comparisons among the survey groups, as post- and latent-expedition groups are more related. McNemar tests could not be used to compare post and latent groups as this data is not paired due to the voluntary and anonymous nature of the surveys. Ecosystem services were only compared between control and latent groups as that question was not asked in the retrospective pre-post survey. Analyses were run separately for each service and threat category to avoid violating the assumption of mutual exclusivity, as several respondents listed more than one threat and/or service. We ran these analyses for the four most common threat categories (Pollution, Climate change, Ocean warming, and Humans) and all ecosystem services except for Medicine to avoid violating the assumption of expected values exceeding 5 in at least 80% of the cells.

We were also interested in comparing the total number of coral reef services and threats listed by survey respondents between surveys. To do so, Shapiro tests were used to determine if the number of coral reef services and threats listed were normally distributed across groups, and all mean comparison analyses required nonparametric tests. A Mann-Whitney U test was used to compare the number of ecosystem services listed between control and latent groups, but not the immediate post-expedition group as this question was not asked in the retrospective pre-post survey. The knowledge of threats question was asked in all three surveys, but as in the knowledge-level analyses, we did not use a single 3-way means comparison of number of threats listed between the control, post-expedition, and latent-expedition groups, because the post- and latent-expedition groups are more related. Therefore, we again used separate Mann-Whitney U tests to compare the number of threats listed between 1) control to post-expedition, 2) control to latent-expedition, and 3) post-to latent-expedition. Again, variance tests and histograms were used to assess if the shape of the distributions of number of threats and number of services listed were similar enough across groups to allow interpretation of results as [non]significant differences between mean ranks. We also used this same procedure to compare number of threats and services listed between individuals who had been on one RAR trip *versus* two or more trips. The variances of the number of services and the number threats listed between 1 RAR trip and 2+ RAR trips, and the number of threats listed between post- and latent-expedition groups were similar allowing interpretation as [non]significant differences in mean ranks for these comparisons. Finally, we used a chi-square analysis to determine if total number of RAR expeditions influenced whether an individual changed (i.e., binary Yes/No response) their perceptions and behaviors because of their interactions with RAR.

3 Results

We received 159 responses from the latent-expedition survey, 239 responses from the control survey, and had 263 responses available from the historical retrospective pre-post surveys (meaning we had 263 paired pre-expedition and post-expedition responses). After accounting for inconsistencies described previously, the final data set used for evaluation consisted of 95 latent-expedition responses, 209 control responses, and 253 pre-post expedition responses. However, not all questions received a response from every respondent as the entire survey was voluntary, and thus these samples sizes varied by question. Power analyses conducted in RStudio package "pwr" using a significance threshold of 0.05, power of 0.9, and effect sizes based on the data from Hesley et al. (2017) indicated that our sample sizes were sufficient for statistical analyses.

3.1 Demographics

Education levels between our latent citizen scientists and control population differed, but both groups' age range and occupation were similar. Only 1.1% of our latent citizen scientists reported "High school graduate, diploma, or equivalent" as their highest level of education whereas this constituted 28.7% of our control respondents (Supplementary Table S1). The largest proportion (41.1%) of latent citizen scientists were >45 years old with 25–34 years old comprising the next largest proportion (28.4%). Our control respondents' ages were very comparable, with most (45.7%) being >45 years old and 25–34 years old as the next largest proportion (24.3%). When asked "Is your schooling and/or job directly related to environmental research, conservation, education, advocacy, policy, or similar?" the majority of latent citizen scientists (64.2%) and control respondents (82.3%) answered "No". When asked if they were a current resident of South Florida., 82.1% of citizen scientists answered "Yes". We did not ask this question to our control respondents as being a Florida resident was a requirement for survey eligibility. Similarly, all latent citizen scientists had participated in RAR so, control respondents were asked "Have you participated in an environmental citizen science project before?" and 12.0% answered "Yes". The majority of the control group were not SCUBA divers (89.5%), and most latent citizen scientists had been on more than 50 dives (42.7%), with having logged 1–10 dives comprising the next largest proportion (29.3%).

Looking specifically at our latent citizen scientist audience, we asked how long it had been since they first interacted with our RAR program. There was a tie, with most respondents reporting that it had been either 2 or 3 years (both 35.8%) (Supplementary Table S2). We also asked "How have you interacted with Rescue a Reef?" (i.e., social media, public event, citizen science expedition) and prompted them to check all that apply. Excluding participation in an expedition (as this audience was specific to past participation), the largest proportion of additional program interaction was through social media (42.1%) followed by being an email subscriber (30.5%), presentation attendee (24.2%), donor (22.1%), and public event attendee (18.9%). We also asked how long it had been since their last RAR expedition, and most respondents (48.4%) indicated 2 years. When asked how they participated during their RAR expedition(s), majority (81.1%) of latent citizen scientists answered "SCUBA diver". When asked how many expeditions they have participated in total, majority (65.3%) answered that they had participated in one, 18.9% in two, 10.5% in three, and 5.3% in four or more. When asked if they were interested in participating in future RAR expeditions, majority (94.7%) answered "Yes".

3.2 Perceived knowledge levels

To assess how perceived knowledge levels on coral reef status, ecology, threats, and tools for conservation may have varied depending on group identity and time point, we compared survey scores between control, pre- and post-expedition, and latent-expedition respondents (Figure 1). There was no significant difference in perceived coral reef status between post- and latent-expedition respondents (mean = 2.4 ± 0.9, mean = 2.2 ± 0.7, respectively), but pre-, post-, and latent-expedition means were significantly lower than control response means (mean = 2.7 ± 0.9) (Mann-Whitney U, $p < 0.001$) (Supplementary Table S3). Pre-, post-, and latent-expedition respondents reported having significantly

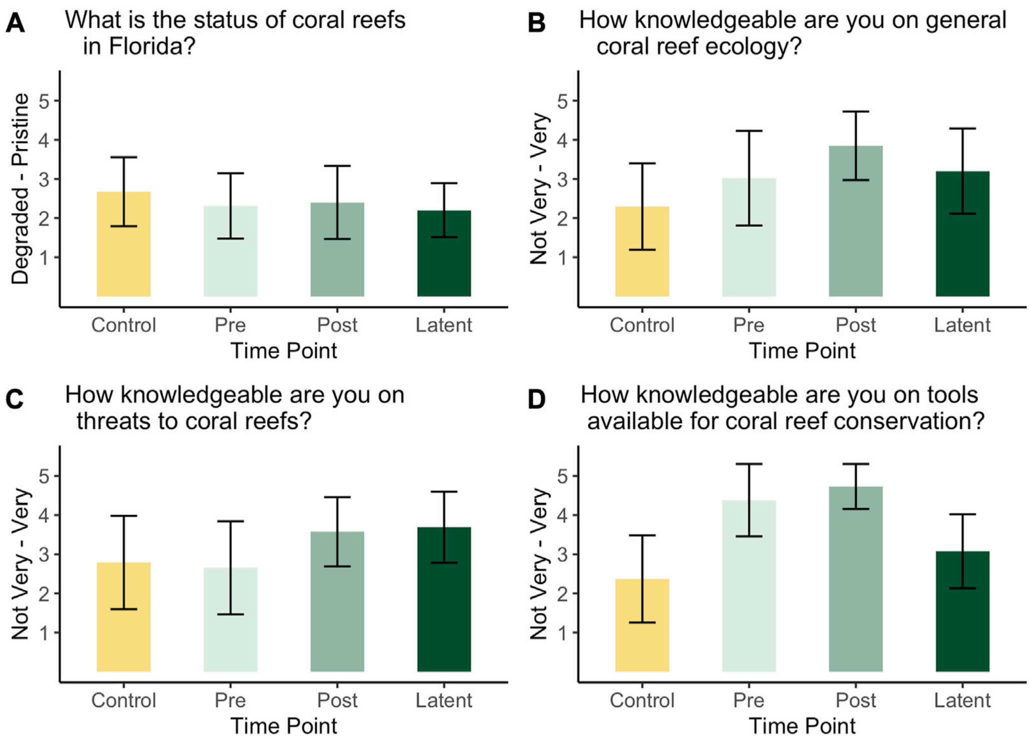

FIGURE 1
Averages (±S.D.) of Likert-scale responses to survey questions assessing perceived knowledge levels on coral reef **(A)** status, **(B)** ecology, **(C)** threats, and **(D)** conservation tools across groups/time points (i.e., pre-expedition, post-expedition, latent-expedition).

higher knowledge levels on coral reef ecology (mean = 3.0 ± 1.2, mean = 3.8 ± 0.9, mean = 3.2 ± 1.1, respectively) when compared to the control group means (mean = 2.3 ± 1.1) (Mann-Whitney U, $p < 0.001$). However, latent-expedition perceived knowledge levels of status were significantly lower than post-expedition respondents (Mann-Whitney U, $p < 0.001$). There was no significant difference in perceived knowledge levels of threats to coral reefs between control and pre-expedition citizen scientists (mean = 2.8 ± 1.2, mean = 2.7 ± 1.2, respectively) nor between post- and latent-expedition citizen scientists (mean = 3.6 ± 0.9, mean = 3.7 ± 0.9, respectively), but both post and latent groups again had significantly higher means than control response means (mean = 2.8 ± 1.2) (Mann-Whitney U, $p < 0.001$). Lastly, pre-, post-, and latent-expedition respondents reported having significantly higher knowledge levels on tools available for coral conservation (mean = 4.4 ± 0.9, mean = 4.7 ± 0.6, mean = 3.1 ± 0.9, respectively) when compared to the control group means (mean = 2.4 ± 1.1) (Mann-Whitney U, $p < 0.001$). However, latent-expedition perceived knowledge levels were again significantly lower than post-expedition respondents (Mann-Whitney U, $p < 0.001$). While the means of the control group and pre-expedition group were significantly different for coral reef status, ecology, and tools for conservation, the groups compared similarly as both identified reef status as below average (mean ≤3) and identified themselves as average-below average in coral ecology (mean ≤3). Additionally, their means for knowledge on threats facing coral reefs were not significantly different.

To assess perceptions on coral conservation actions, we asked both our control group and latent citizen scientists to rank a set of solutions adapted from Kleypas et al. (2021) in order of importance (1 = most important, 6 = least important) (Figure 2). There were six solutions presented to the respondents: land-based pollution reduction, coral reef restoration, addressing climate change, marine protected areas, public education and stewardship, and fisheries management. The top ranked coral conservation action was significantly dependent upon survey group (Chi-square, $\chi 2 = 49.45$, $p < 0.001$) (Supplementary Table S4A). Addressing climate change was ranked as the most important action by the majority (55.8%) of latent citizen scientists and was significantly more likely to be assigned a rank of 1 *versus* any lower value (2+) by the latent group (Chi-square, $\chi 2 = 34.306$, $p < 0.001$), whereas it was the third most important action according to the control population (mean = 3.3 ± 1.7). Land-based pollution reduction was the second most important action according to latent citizen scientists (mean = 2.8 ± 1.3). Most control respondents (30.1%) ranked land-based pollution reduction as the most important action and were significantly more likely to assign pollution reduction the highest rank of 1 *versus* any lower value (2+) (Chi-square, $\chi 2 = 9.763$, $p < 0.05$) (Supplementary Table S4B). The control group was also significantly more likely to assign reef restoration a rank of 1 *versus* any lower value (2+) (Chi-square, $\chi 2 = 11.635$, $p = 0.001$). When considering the mean rank values, coral reef restoration was the top priority for control respondents (mean = 2.5 ± 1.3) and land-based pollution was second (mean = 2.6 ± 1.5). Latent citizen scientists ranked coral reef restoration third (mean = 3.5 ± 1.5), public education and stewardship fourth (mean = 3.7 ± 1.8), marine protected areas fifth (mean = 3.9 ± 1.3), and fisheries management sixth (mean = 4.9 ± 1.4). Control respondents also ranked fisheries management sixth but re-prioritized fourth and fifth.

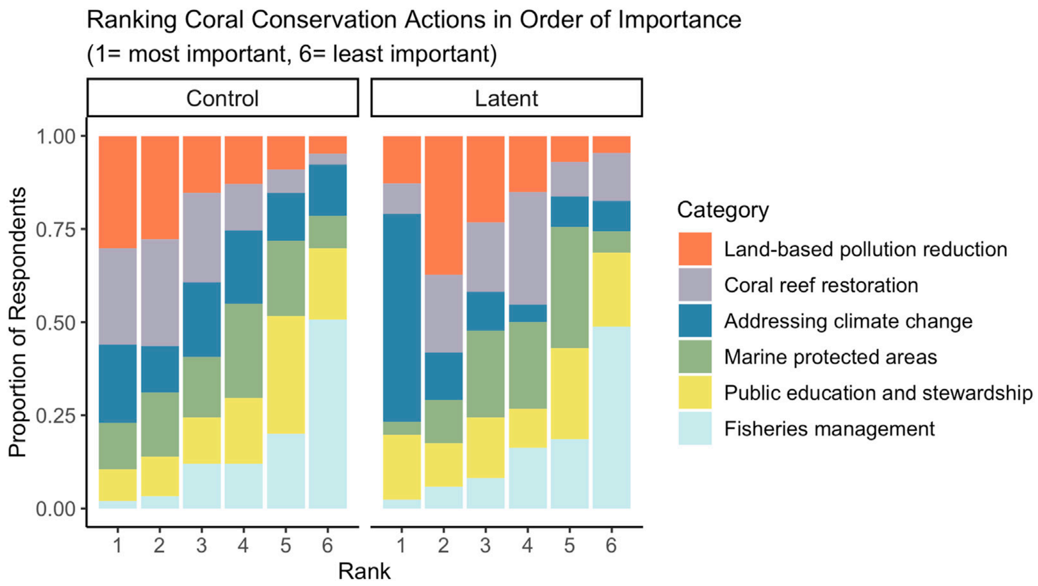

FIGURE 2
Proportion of survey respondents that ranked various coral conservation activities in order of importance from 1 (most important) to 6 (least important), compared between the control and latent citizen scientist group.

3.3 Knowledge levels

To assess knowledge levels on the issues facing coral reefs as well as the ecosystem services they provide, we asked both our control group and latent citizen scientists to provide specific examples through open-ended questions. We were also able to source survey responses from post-expedition citizen scientists on the topic of coral reef threats but not services.

When asked "What ecosystem services do coral reefs provide?", the greatest proportion of both the control group and latent-expedition respondents answered habitat (HOM) (26.3% and 46.3%, respectively) (Figure 3A). A high proportion (45.3%) of latent-expedition respondents also answered coastal protection (PRO), followed by supporting food webs (FF) (20.0%) and providing food for humans (EAT) (16.8%). No other response was above 15%, and 25.3% could not produce an answer. After habitat for marine organisms, the control group said coral reefs support biodiversity (BIO) in the next highest proportion (18.2%). No other response was above 15%, and 22.0% could not produce an answer. Comparing between groups, the frequency of a service being listed by latent citizen scientists was significantly higher for habitat, coastal protection, human food source, economic driver (DOL), and nursery (NUR) (Figure 3A) (Chi-square, $\chi2 = 11.896$, $p < 0.001$, Chi-square, $\chi2 = 66.251$, $p < 0.001$, Chi-square, $\chi2 = 8.54$, $p < 0.05$, Chi-square, $\chi2 = 14.96$, $p < 0.001$, Chi-square, $\chi2 = 16.99$, $p < 0.001$, respectively) (Supplementary Table S5A). The frequency of a service being listed by the control group was significantly higher for biodiversity and oxygen (OXY) as well as for wrong answers (WR) (Chi-square, $\chi2 = 3.79$, $p = 0.05$, Chi-square, $\chi2 = 4.698$, $p < 0.05$, Chi-square, $\chi2 = 5.41$, $p < 0.05$, respectively). The frequency of food webs and water filtration (CLN) being listed as well as the frequency of no services listed (NR) was independent of survey group (Chi-square, $\chi2 = 3.41$, $p > 0.05$, Chi-square, $\chi2 = 0.33$, $p > 0.05$, Chi-square, $\chi2 = 0.39$, $p > 0.05$, respectively). Our retrospective pre-post expedition survey does not include this question so their knowledge levels on this topic could not be assessed.

When asked "What are the largest issues facing coral reefs?", majority (55.6%) of post-expedition respondents answered pollution (POL) whereas most (48.4%) of the latent-expedition citizen scientists said ocean warming (OW) specifically (Figure 3B). The greatest proportion (40.2%) of the control group also felt pollution was one of the largest threats facing reefs. Post-expedition respondents then answered climate change (CC) in the second highest proportion (41.7%) followed by ocean warming (36.1%) more specifically and then humans (HUM) (29.2%). No other response was above 20%, and 16.7% could not produce an answer. After ocean warming, latent-expedition answered climate change (45.3%), pollution (42.1%), humans (29.5%), and ocean acidification (OA) (22.1%) in the highest proportions. No other response was above 20%, and 17.9% could not produce an answer. After pollution, the control group said humans were the largest issue facing coral reefs (30.1%). No other response was above 20%, and 15.8% could not produce an answer. Comparing between control and post-expedition respondents, the frequency of a threat being listed by post citizen scientists was significantly higher for pollution, climate change, and ocean warming (Chi-square, $\chi2 = 5.127$, $p < 0.05$, Chi-square, $\chi2 = 31.427$, $p < 0.001$, Chi-square, $\chi2 = 32.340$, $p < 0.001$, respectively) but not for humans (Chi-square, $\chi2 = 0.024$, $p > 0.05$) (Supplementary Table S5B). Comparing between control and latent-expedition groups, the frequency of a threat being listed by latent citizen scientists was significantly higher for climate change and ocean warming (Chi-square, $\chi2 = 43.375$, $p < 0.001$, Chi-square, $\chi2 = 64.523$, $p < 0.001$, respectively), but not for pollution nor humans (Chi-square, $\chi2 = 0.09905$, $p > 0.05$, Chi-square, $\chi2 = 0.014$, $p > 0.05$, respectively) (Supplementary Table S5C). The frequency of no threats listed (NR) was independent of survey group (Chi-square between control and post, $\chi2 = 0.03$, $p > 0.05$, control and latent, $\chi2 = 0.21$,

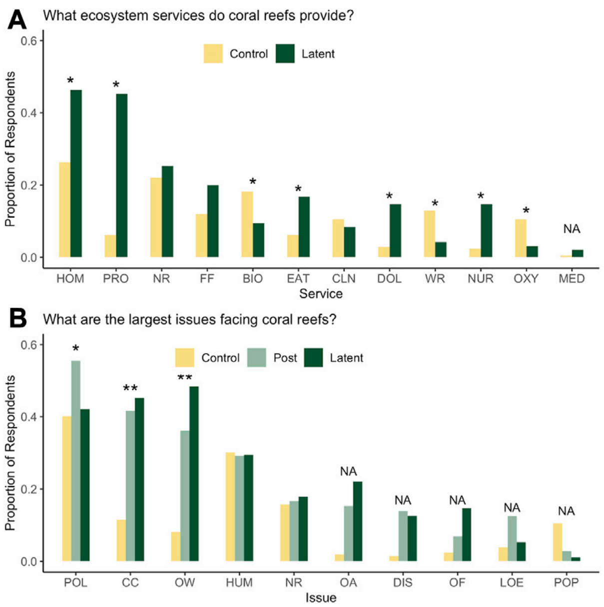

FIGURE 3
(A) Proportion of survey responses across groups/time points mentioning each theme to open-ended questions on ecosystem services provided by coral reefs: 1) HOM = habitat, 2) PRO = coastal protection, 3) NR = no response, 4) FF = food webs, 5) BIO = biodiversity, 6) EAT = human food source, 7) CLN = water quality, 8) DOL = economic driver, 9) WR = wrong, 10) NUR = nursery, 11) OXY = oxygen, 12) MED = medicine. Single asterisks (*) indicate a significant relationship between frequency of the category listed and survey group (control *versus* latent) per Chi-square analyses. **(B)** Proportion of survey responses across groups/time points mentioning each theme to open-ended questions on largest issues facing coral reefs: 1) POL = pollution, 2) CC = climate change, 3) OW = ocean warming, 4) HUM = humans, 5) NR = no response, 6) OA = ocean acidification, 7) DIS = disease, 8) OF = overfishing, 9) LOE = lack of education, 10) POP = population scarcity. Single asterisks (*) indicate a significant relationship between frequency of the threat listed and control *versus* post-expedition groups, and double asterisks (**) indicate a significant relationship between the threat listed and both 1) control *versus* post-expedition groups and 2) control *versus* latent-expedition groups. "NA" labels indicate that expected values were too small to run Chi-square analyses.

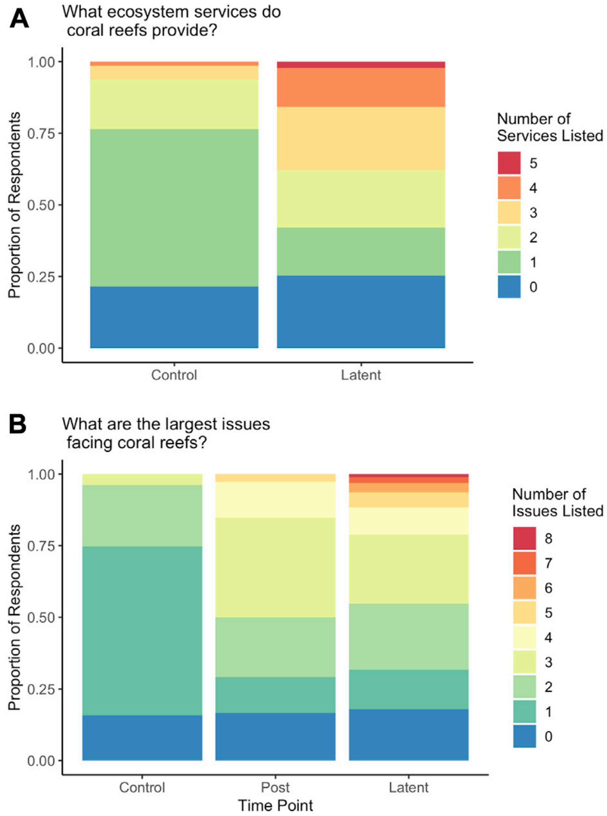

FIGURE 4
Proportion of the total number of accurate responses provided by survey respondents to open-ended questions on both **(A)** ecosystem services provided by coral reefs and **(B)** largest issues facing coral reefs compared between survey groups/time points.

$p > 0.05$, post and latent, $\chi 2 = 0.04$, $p > 0.05$). Comparing threat frequencies between post- and latent-citizen science groups did not produce significant results (Supplementary Table S5D).

Counting the total number of responses provided allowed us to assess the breadth as well as the depth of their knowledge levels. When asked about the ecological services coral reef provide, latent citizen scientists were able to provide significantly more answers than the control group (mean = 1.9 ± 1.5, mean = 1.1 ± 0.8, respectively) (Mann-Whitney U test, $p < 0.001$) (Supplementary Table S6A). While majority (57.9%) of latent-expedition citizen scientists produced two or more answers, only 23.4% of the control group was able to (Figure 4A). Majority (55.0%) of the control group produced one answer. The total number of services listed was not significantly dependent upon how many RAR expeditions (one *versus* 2+) an individual had participated in (Mann-Whitney U test, $p > 0.05$) (Supplementary Table S6A).

When asked about the issues facing coral reefs, both post- and latent-expedition citizen scientists were able to provide significantly more answers (mean = 2.2 ± 1.4, mean = 2.4 ± 1.8, respectively) than the control group (mean = 1.1 ± 0.7) (Mann-Whitney U test, $p < 0.001$) (Supplementary Table S6B). The greatest proportion of both the post-expedition (34.7%) and latent-expedition (24.2%) citizen scientists produced three threats facing coral reefs whereas majority (58.9%) of the control group only produced one answer (Figure 4B). Furthermore, majority of both post-expedition (70.8%) and latent-expedition (68.4%) respondents produced two or more answers, while only 25.4% of control respondents were able to. The total number of RAR expeditions an individual participated in (one *versus* 2+) did not significantly impact the number of issues listed by latent citizen scientists (Mann-Whitney U test, $p > 0.05$) (Supplementary Table S6B).

3.4 Social change

When asked how confident participants are in their ability to communicate coral reef-related topics to others on a scale of 1 = Not very to 5 = Very, latent citizen scientists were significantly more confident than the control group (mean = 3.3 ± 1.1, mean = 2.6 ± 1.3) (Mann-Whitney U test, $p < 0.001$) (Supplementary Table S7A). Nearly half (42.7%) of latent citizen scientists felt confident in their communication skills compared to only 24.9% of the control group

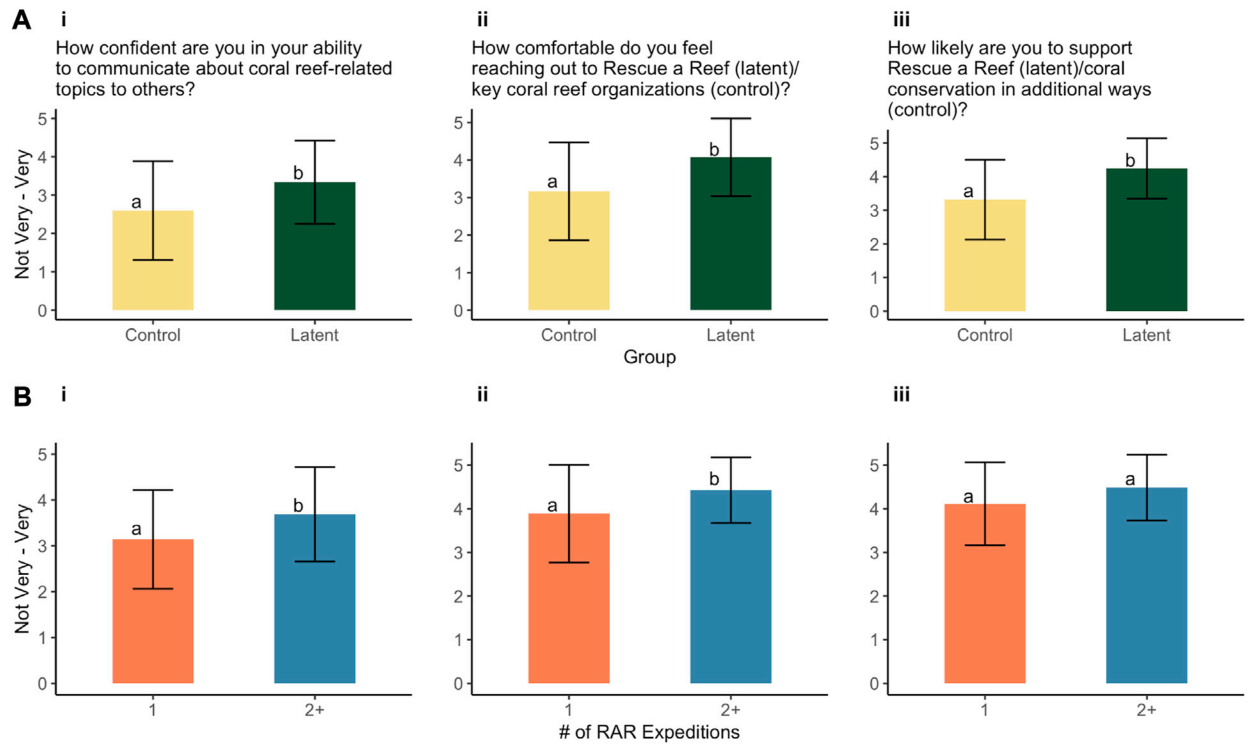

FIGURE 5
Averages (±S.D.) of Likert-scale surveys response across **(A)** groups and **(B)** total number of Rescue a Reef expeditions participated in for **(i)** comfort communicating coral reef-related topics to others, **(ii)** comfort reaching out to Rescue a Reef/coral conservation organizations, and **(iii)** likelihood of supporting Rescue a Reef/coral conservation organizations in additional ways. Letter annotations indicate a significant relationship between survey groups/number of RAR expeditions and Likert-scale responses per Mann-Whitney U tests.

(Figure 5A). Furthermore, only 2.2% of the latent group said they were "not very" confident in their abilities whereas 23.9% of the control group felt this way. Interestingly, individuals who had been on 2 or more RAR expeditions were significantly more confident in their ability to communicate on coral reef-related topics compared to individuals who had only been on one trip (Mann-Whitney U test, $p < 0.05$) (Supplementary Table S7B).

When asked how comfortable they feel reaching out to "key coral reef organizations" (control) or "Rescue a Reef" (latent-expedition) if they have a question, latent citizen scientists were significantly more comfortable than the control group (mean = 4.1 ± 1.0, mean = 3.2 ± 1.3) (Mann-Whitney U test, $p < 0.001$) (Supplementary Table S7A). Majority (70.5%) of latent citizen scientists felt comfortable contacting RAR with 46.3% saying they were "very" comfortable, whereas 41.6% of the control group felt they could reach out to another similar coral conservation organization with only 19.6% saying they were "very" comfortable (Figure 5A). Conversely, only 1.1% of latent citizen scientists said they were "not very" comfortable reaching out to RAR. Notably, individuals who had been on 2 or more RAR expeditions were significantly more comfortable reaching out compared to individuals who had only been on one (Mann-Whitney U test, $p < 0.05$) (Figure 5B) (Supplementary Table S7B).

When asked how likely they are to support "coral conservation" (control) or "Rescue a Reef" (latent-expedition) in additional ways (i.e., volunteering, donating, advocating), latent citizen scientists were again significantly more likely to compared to the control group (mean = 4.2 ± 0.9, mean = 3.3 ± 1.2) (Mann-Whitney U test, $p < 0.001$) (Supplementary Table S7Aa). Majority (75.5%) of latent citizen scientists said they were likely to support RAR in additional ways with over half (52.1%) saying they were "very" likely to, whereas only 20.1% of the control group said they were "very" likely to support a coral conservation organization (Figure 5A). Zero percent of latent citizen scientists said that they were "not very" likely to support RAR again, and only 3.2% said they were unlikely to. Likelihood of supporting RAR in additional ways was not significantly impacted by number of RAR expeditions (Mann-Whitney U test, $p > 0.05$) (Figure 5B) (Supplementary Table S7B).

To determine our program's impact on citizen scientists 1+ years after they participated in our coral restoration expedition, we asked them to candidly reflect on if and how their perceptions and behaviors changed because of RAR. When asked "Have your perceptions of coral reefs changed because of your interaction(s) with Rescue a Reef?", majority (70.5%) of latent citizen scientists answered "Yes" and 26.3% answered "No" (3.2% did not answer). Those who answered yes were asked to describe what perception(s) have changed. A few common themes emerged such as a realization of the importance of corals:

> "When you are able to hands-on interact with coral you begin to understand how the coral is extra special/unique and when placed within its ecosystem how it serves the piece of the larger picture,"

> "I have an even greater appreciation for our reefs than I had before and I want to help make a difference,"

> "Made me more aware of importance of reefs as well as impact from global warming on reefs (and thus I did more research) . . . Participating in reef restoration made me feel more connected and protective of reef ecosystems,"

> "Increased appreciation for the importance of a healthy reef system and our ability to restore and grow reefs in affected areas,"

The need for action to through advocacy and stewardship:

> "[My perceptions] changed in a way that we must continue to strongly advocate for our oceans the same way we do for other issues that exist in our society,"

> "I've realized the reefs need more attention than I was aware of, and that we can all make changes that will help,"

> "How important we humans are to protect the coral reefs,"

And a newfound hope for their future:

> "Prior to participating, I had very little knowledge of coral restoration–I now feel more hopeful about our collective ability to help restore reef ecosystems,"

> "I better understand how coral reefs support not only life in the ocean, but how they also support life on land by providing habitat for our food and protection of our coastlines. Rescue a Reef taught me tangible ways to help and support reef health and provides hope for the future,"

> "I have more hope for the future of coral reef health and conservation."

When asked "Have your behaviors/actions changed because of your interaction(s) with Rescue a Reef?", the majority (61.1%) of latent citizen scientists answered "Yes" and 34.7% answered "No" (4.2% did not answer). Those who answered yes were asked to describe what behavior/action(s) have changed. Most (35.2%) responded that they were better advocates for coral reefs (COMM) following their experience with RAR (Figure 6). This included increased communication, advocacy, and knowledge-sharing with others. The next most common behavioral change was living an eco-friendlier lifestyle (ECO) with 18.5% of respondents. This included answers related to lowering their carbon footprint, choosing more eco-friendly products and brands, and increased conscientiousness on sustainability. Latent-expedition citizen scientists also reported volunteering (VOL) (16.7%), reducing, reusing, and recycling (RRR) (13.0%), and reef-safe sunscreens (SUN) (16.7%) as new behaviors taken up because of interacting with RAR. It should be noted that roughly one-fifth (20.4%) of those who reported a behavior/action change did not provide a response (NRL), negatively skewing the other categories' proportions. Nonetheless, of those who reported a behavior/action change, 31% listed two or more changes.

The total number of RAR expeditions had a significant influence on perception change, with individuals who had participated in 2 or more excursions indicating that their perceptions had changed as a result of interacting with RAR (Chi-square, $\chi 2 = 5.89$, $p < 0.05$) (Figure 7A). There was no significant association between reported behavior change (Yes/No) and total number of RAR expeditions one had participated in (Chi-square, $\chi 2 = 0.796$, $p > 0.05$) (Figure 7B).

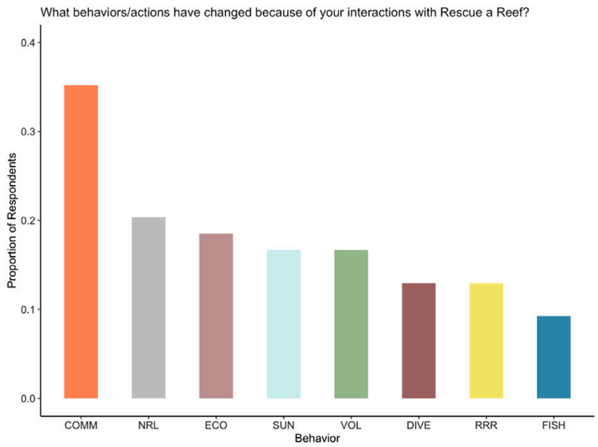

FIGURE 6
Proportion of latent citizen scientist survey responses mentioning each behavioral theme that changed because of their interaction(s) with Rescue a Reef: 1) COMM = advocacy, NRL = no response listed, ECO = eco-friendly life choices, SUN = reef-safe sunscreens, VOL = volunteering, DIVE = responsible diving habits, RRR = reduce/reuse/recycle, FISH = responsible fishing/boating habits.

4 Discussion

This longitudinal evaluation of the RAR citizen science coral restoration program serves as an important first attempt to assess the long-term impacts of the activities. While community-based restoration programs can be a powerful platform for education and stewardship as well as increase project capabilities and success, few programs utilize citizen science and even fewer evaluate the impacts (Hernández-Delgado et al., 2014; Hein et al., 2019; Goergen et al., 2020; Suggett et al., 2023). Here, we attempt to model how nature-based citizen science activities can benefit coral reefs and community members alike.

First, our evaluation revealed a strong sense of community and coral stewardship among our RAR latent citizen science participants, with the majority of individuals having engaged the program for three or more years. Additionally, majority were comfortable contacting us if needed and reported that they were very likely to support RAR in additional ways (i.e., volunteering, donating, advocating) (Figure 5A). Importantly, the high likelihood to continue contributing to RAR in additional ways was not significantly affected by number of RAR expeditions they participated in which suggests strong support for the program and its mission after only one interaction. This was further emphasized by the vast majority (94.7%) responding that they were interested in participating in a future RAR citizen science expedition. In addition to joining us on an expedition, most also follow RAR on social media with many also having subscribed to the

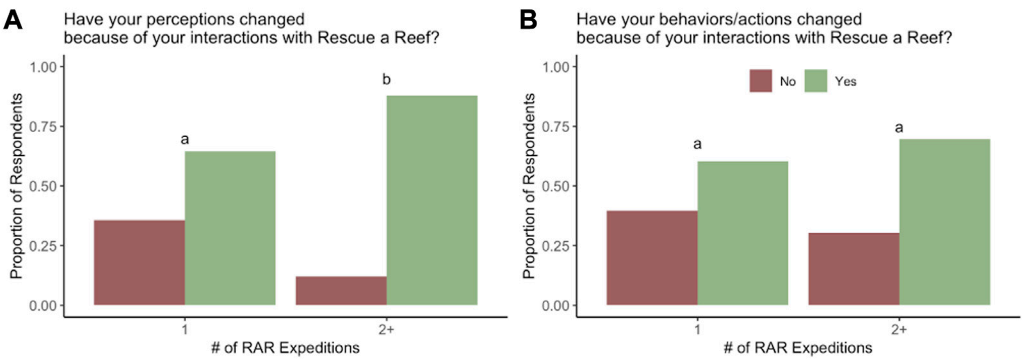

FIGURE 7
Proportion of survey respondents that indicated if they changed their **(A)** perceptions and **(B)** behaviors/actions because of their interactions with Rescue a Reef. Letter annotations indicate a significant relationship between number of Rescue a Reef expeditions and change (Yes/No) per Chi-square analysis.

email list, attended public presentations, and/or donated to RAR. Latent citizen scientists have also become strong stewards with most reporting that they were better advocates for coral reefs following their interactions with RAR and feeling significantly more confident in their ability to communicate coral reef-related topics when compared to the control group. The high retention rates, sense of community, and increased stewardship observed here among participants are all essential metrics of success for building capacity within a community-based coral restoration program (Goergen et al., 2020).

Second, we demonstrated that our latent citizen scientists largely retained their knowledge levels on coral reef-related topics despite the passing of time. Hesley et al. (2017) established that there were perceived knowledge gains by citizen scientists following participation in a RAR coral restoration expedition so it was important to assess if these gains were sustained over time. The latent citizen scientists had significantly higher self-reported knowledge levels on coral reef ecology, threats, and tools available for conservation when compared to the control group. The same was true when comparing post-expedition citizen scientists to the control group. This would suggest that our citizen scientists maintained above-average knowledge levels (mean ≥ 3) on these topics even though 1–6 years had passed. Conversely, our control group reported below-average knowledge levels (mean ≤ 3) on coral reef ecology, threats, and tools available for conservation suggesting a need for more community engagement with the general public through citizen science activities like RAR. Importantly, our post- and latent-citizen scientists also better understood the degraded status of coral reefs compared to the control group, who assigned them a significantly higher health score. When asked about the ecological services coral reefs provide, latent citizen scientist respondents were able to provide significantly more correct answers than the control group. In fact, majority were able to produce two or more and accurately identified habitat, coastal protection, human food source, economic driver, and nursery as ecological services at a significantly higher frequency than the control group. This was also observed when asked about the threats facing coral reefs, with latent respondents providing significantly more correct answers and listing climate change and ocean warming at a significantly higher frequency than the control group. Again, a majority of the latent citizen scientists produced two or more responses while only 25.4% of the control group did so. Conversely, there was no significant difference between the frequency of responses provided by post- and latent-expedition citizen scientists when answering threats facing coral reefs suggesting that knowledge was largely retained.

Third, our evaluation illustrated the potential of citizen science to act as a vehicle for social change, positively reshaping participant perceptions and behaviors. The majority of our latent citizen scientists reported that they have had changes in perceptions because of their interactions with RAR. This included, but was not limited to, their understanding of coral reefs, emotional connection to the cause, and hope for the future. This is important as how messaging and citizen science experiences elicit emotion and make people feel plays a critical role in fostering future environmental engagement (Moser, 2010; Dean et al., 2018). Our evaluation suggests RAR activities are promoting this engagement among participants as a majority of latent respondents reported that they have changed their behavior because of their interactions with the program. When asked what behaviors/actions changed, most responded that they were better advocates for coral reefs through increased communication, advocacy, and knowledge-sharing with others. They also reported changes in their lifestyle and sustainability choices, volunteer contributions, and reduce, reuse, recycle habits. While these actions may seem insignificant, individuals can feel overwhelmed and/or helpless when confronted with climate change and the issues it causes so meeting them where they are is an important first step (Moser, 2010; Gifford, 2011).

4.1 Fostering community and stewardship

Citizen science and community-based organizations like RAR exist to serve the needs of the community. But building a sense of community and stewardship does not happen overnight, it requires time and community buy-in (Kloos et al., 2012). When individuals feel a sense of belonging within these organizations, they become more invested in its goals, influential in its direction, emotionally connected to the cause, and responsible for its success (Arnstein, 1969; McMillan and Chavis, 1986; Kloos et al., 2012; Bela et al., 2016; Goergen et al., 2020). Community members are more likely to change their perspectives and actions if they are able to understand and reflect on their relevant behaviors and roles in the organization (Bonney et al., 2016).

However, the historical focus of restoration practitioners on the short-term ecological benefits of coral restoration has limited the potential for socio-ecological benefits through public engagement, participation, and collaboration (Suggett et al., 2023). While many coral restoration practitioners emphasize the need to consider social, economic, and cultural factors in the evaluation of restoration projects, few actually do in praxis (Hein et al., 2017; Ferse et al., 2021). This represents a juxtaposition as key-informant interviews with coral restoration project stakeholders identified "socio-cultural benefits" as the most frequently mentioned product of coral restoration programs (Hein et al., 2019). Furthermore, the stakeholders directly involved in those restoration activities reported significantly higher project appreciation and positive experiences, highlighting the potential impacts of hands-on participation. Conversely, the same study identified "disconnect with local community" as the second-most frequently mentioned problem with coral restoration projects. And while a survey by Ferse et al. (2021) of 50 coral transplantation projects found that over half included some form of education and public awareness, the level of community engagement was unclear and not ubiquitous leading the authors to suggest it be made an integral part of any coral restoration project. As observed here, addressing this disconnect presents a unique opportunity for restoration practitioners to realize additional socio-ecological benefits and reach critical coral conservation goals.

An important factor of citizen science is the transition from casual contributors to sustained community members. Jackson et al. (2015) described an arc of participation, beginning with knowledge acquisition, then knowledge dissemination, and finally increased participation, ultimately leading to program success and impact. Evidence suggested that many participants first volunteered for the citizen science project to develop a sense of identity and connect with the project community. As the participant continued to engage with the project community their self-efficacy improved leading to additional engagement. The authors noted that participants gradually start to identify with the underlying project ideology and begin to feel part of the community. Our evaluation supports this as latent citizen scientists who had participated in two or more expeditions were significantly more comfortable reaching out to RAR and significantly more confident in their ability to communicate coral reef-related topics than those who had only participated in one. Furthermore, latent respondents who had participated in two or more expeditions were significantly more likely to report that their perceptions had changed as a result of interacting with RAR. This suggests that sustained engagement and participation in RAR citizen science activities can foster community, confidence, and social change.

While Hein et al. (2019) found that a majority of coral restoration project volunteers and interns in their study were visiting tourists, a majority (82.1%) of our latent citizen scientists were Florida residents. This is important as community-based restoration projects can heighten community awareness and foster stewardship for local reef resources (Kittinger et al., 2016). This was observed in our evaluation too as latent citizen scientists were significantly more confident in their ability to communicate coral reef-related topics than the control group. Furthermore, increased communication and advocacy for coral reefs was the most common behavioral change reported by citizen scientists. Our results suggest their role as communicators could have meaningful, positive impacts on the greater community too as latent citizen scientists were able to provide significantly more correct open-ended responses overall and in higher frequencies on the importance of coral reefs and the issues they face when compared to the control group. Citizen science is capable of fostering a community of "opinion leaders" or individuals who are motivated to address issue-specific concerns by taking concrete action and advocating on the issues (Johnson et al., 2014). This form of communication and dissemination can be "contagious" too, leading to higher overall community awareness. Scientists have been sounding the alarm on climate change for decades under the assumption that informing and educating the public would lead to action but the unique nature of the climate problem (i.e., invisible causes, distant impacts) has defied this assumption (Moser, 2010). Instead, scientists must work to address these problems through relevant communication and supporting mechanisms, which we demonstrate here through direct community engagement and citizen science. By building community and confidence among citizen scientists, there is the potential to mobilize individuals in a more far-reaching and impactful way.

A common criticism of citizen science is that volunteers tend to be self-selected and may not well represent the entire population (Jordan et al., 2011; Crall et al., 2013). Therefore, if a project seeks to improve attitudes and/or behavior it must engage new audiences who are not as knowledgeable on the subject and reframe it from a volunteer effort to a community-led effort (Brossard et al., 2005; Bela et al., 2016). Our evaluation suggests RAR had some success on this front as majority of latent citizen scientists said that their schooling or job was not related to environmental research, conservation, education, or otherwise. This was in part due to a concerted effort by RAR to engage non-environmental community groups and stakeholders like the veterans of The Mission Continues, Royal Caribbean Group of the cruise line industry, private sector entrepreneurs at WeWork, among others. Rescue a Reef also strives to increase the accessibility of its citizen science opportunities by significantly subsidizing the typical costs associated with snorkel or SCUBA dive excursions through external sponsors and by collaborating with groups working to build diversity and dismantle barriers in marine science like Black in Marine Science. Collaborating with both diverse and local communities is critical to addressing inequalities and inefficiencies in both coral and citizen science (Bela et al., 2016; Suggett et al., 2023). One of the most valuable components of citizen science programs is the relationship between the practitioners, the citizens, and the process of their work (Bond et al., 2016). The work itself creates a dialogue through which important issues are identified and addressed collaboratively, much like symbiotic relationships in nature (Bela et al., 2016). By integrating research with action, our citizen science-based work is better able to understand and enhance the quality of life for individuals, communities, and societies we serve.

4.2 Knowledge gaps

The majority of latent citizen scientists ranked addressing climate change as the most important action for coral conservation, the frequency they answered climate change as a threat to coral reefs was significantly higher than the control group, and they were significantly more likely to rank it as the most important action *versus* any lower value (i.e., 2+). However, this was third most important action according to the control group. Instead, most control respondents considered land-based pollution reduction the most important thing to address and were significantly more likely to rank it as the top priority over other coral conservation actions. The fact latent citizen scientists identified addressing climate change as the most important tool is significant, as expert consensus maintains that mitigating greenhouse gas emissions is both essential to coral reef survival and the most wide-reaching, effective, and achievable action (Kleypas et al., 2021). Furthermore, it addresses a common criticism among the broader coral scientist community that coral restoration practitioners frame their activities as the most important action for coral recovery. However, our latent citizen scientists importantly identified the need to act on both local and global stressors in conjunction with reef restoration. We prioritize this messaging both during and following our expeditions as studies have shown procedural learning is strongly associated with increased support for marine conservation and new behavioral intentions (Dean et al., 2018). This was borne out through the open-ended questions too, with most (48.4%) latent citizen scientists answering that ocean warming specifically is the largest issue facing coral reefs, followed by climate change (45.3%) more broadly, pollution (42.1%), direct human impact (29.5%), and ocean acidification (22.1%) in the next highest proportions. This presents an important shift in priorities as majority of post-expedition citizen scientists answered that land-based pollution was the largest issue facing reefs, not climate change, suggesting latent citizen scientists are now in better alignment with coral expert consensus (Hoegh-Guldberg et al., 2019; Boström-Einarsson et al., 2020; Ferse et al., 2021; Kleypas et al., 2021; Suggett et al., 2023).

There was no significant difference in the perceived status of coral reefs between post-expedition respondents and latent citizen scientists, with both groups identifying coral reefs as "degraded". However, both post- and latent-expedition means were significantly lower than the control group's mean, suggesting there is a slight disconnect between our RAR community members and Florida residents. Nonetheless, this evaluation and previous literature indicate that Floridians have a fair understanding of the degraded state of coral reefs (Hesley et al., 2017; Allen et al., 2021). This would suggest that coral scientists, managers, restoration practitioners, *etc.*, should refocus their communication strategies to the specific threats facing reefs and associated tools available for conservation and recovery through "ocean optimism" messaging rather than doom and gloom (Knowlton, 2021). This is further emphasized in our findings that latent citizen scientists reported significantly lower knowledge levels on tools available for coral conservation than the post-expedition respondents, suggesting they felt less certain over time about what they could do to address coral reef degradation. But by completing this evaluation and identifying this disconnect, we can work to adapt and improve our communication strategies and conservation toolkits.

Another disconnect we observed between the latent citizen scientist and control responses was how they viewed and valued coral reefs. Many (45.3%) latent respondents said that coral reefs are important for coastal protection whereas only 6.2% of the control respondents produced that answer. Furthermore, latent citizen scientists listed habitat, coastal protection, human food source, economic driver, and nursery at significantly higher frequencies than the control group. This could suggest a need for improved educational strategies like citizen science to convey the roles and value of Florida's Coral Reef to residents. The U.S. ranks within the top 10 of countries in the number of people that may receive risk reduction benefits from reefs with an estimated 3 million individuals (Ferrario et al., 2014). Furthermore, the annual value of flood risk reduction provided by U.S. coral reefs is more than 18,000 lives and $1.8 billion dollars (Storlazzi et al., 2019). There is a need to broaden public discourse to include our growing understanding of ecosystem services' role in the safety and wellbeing of communities if we hope to see a shift perceptions and values (Costanza et al., 2017). The practical portion of our program (i.e., coral gardening and reef restoration) is aimed at providing community members with the opportunity to actively help mitigate impacts and recover depleted resources which has been shown to develop ownership of said resources and the empowerment of learners, a critical component of social change (Phillips et al., 2019).

4.3 Need for evaluation

It is not enough to assume a service is achieving intended benefits and/or changes are realized. There is a clear need for citizen scientist practitioners to better understand the importance and implications of addressing social issues through research and action (Brossard et al., 2005; Bonney et al., 2009; Crall et al., 2013). Program evaluation can consume time and resources but can also help validate the services provided as well as the intended outcomes (Gill, 2010; Posavac, 2011; Bela et al., 2016). Without evidence of a project's outcomes, practitioners are left with a critical gap in understanding the effectiveness and potential impact of the activities (Gill, 2010; Posavac, 2011; Bela et al., 2016). Over a decades-worth of coral restoration data has proven the process effective (Schopmeyer et al., 2017). Then, Hesley et al. (2017) demonstrated the ecological contributions citizen scientists can have when working in collaboration with trained restoration practitioners. Here, the sociocultural impacts observed create a more comprehensive evaluation of the effectiveness of citizen science for coral conservation and restoration in social-ecological dimensions (Hein et al., 2017; Goergen et al., 2020).

Coral reef restoration activities must consider the relationship between stakeholders, goods and services, and the environment itself when measuring success (Goergen et al., 2020; Suggett et al., 2023), something that is only achievable when communicating and collaborating with community members through avenues like citizen science. Continued investment into coral restoration activities requires evidence of its benefits and value, not least of which are the social impacts as described here. These long-term benefits of integrating citizen science coral restoration activities make a strong argument for additional investment by local governments and stakeholders alike (Ferse et al., 2021; Suggett et al., 2023). Citizen science can also act as an important vehicle for closing funding gaps through other direct (i.e., volunteers, donations) and indirect (i.e., in-kind contributions, media ad equivalency) sources of support (Hesley et al., 2017; Bayraktarov et al., 2020; Ferse et al., 2021). This evaluation helps highlight the numerous strengths and benefits of RAR's community-based programming as well as the justification for increased and sustained support.

Between 2015–2017, community members who participated in a RAR citizen science expedition reported significant improvements in coral reef ecology and restoration knowledge post-expedition (Hesley et al., 2017). Additionally, corals outplanted by citizen scientists showed the same survivorship as those outplanted by trained coral restoration practitioners. Both are important metrics of success for building capacity and stewardship through education and outreach within a community-based coral restoration program (Goergen et al., 2020). To date, RAR has hosted >100 citizen science expeditions with >1,000 community members having helped restore >10,000 coral colonies onto Florida's Coral Reef. What is not considered in this evaluation of RAR's citizen science activities is the thousands more individuals regularly engaged through their education, outreach, and online activities like classroom presentations, laboratory tours, and social media campaign. Through these activities in combination with their citizen science expeditions, the RAR program has successfully fostered a broad community of coral reef champions. It is difficult to formally assess the value or worth of this, but one can easily recognize its potential as a powerful platform for raising awareness and promoting action for the conservation and restoration of our oceans. We hope the information and impact observed through this program evaluation will motivate more individuals, organizations, and institutions to incorporate community engagement and citizen science into their activities to advance their own mission and goals.

4.4 Moving forward

Globally, we are seeing environmental and ecological collapse due to our changing climate. This is a humanitarian crisis as the planet's ecosystems, environments, and biodiversity are essential to the sustainability of our species. The biodiversity of tropical rainforests and coral reefs provide critical support for drug discovery and the availability of life-saving medicines (Mendelsohn and Balick, 1995). Mounting evidence indicates that high biodiversity and ecosystem function frequently prevent disease transmission among humans, animals, and plants (Keesing et al., 2010). Maintaining both species and genetic diversity increases commercial crop yields, fodder yields, and fisheries stability, providing food for billions (Cardinale et al., 2012). Plant species diversity has been shown to increase aboveground carbon sequestration, oxygen production, and nutrient mineralization; all essential to planetary sustainability (Cardinale et al., 2011). Natural environments and species biodiversity has a significant, positive effect on leisure, culture, mental health, and aesthetic value for communities and human wellbeing (Tribot et al., 2016). And natural resources, environmental services, and biodiversity play an important role in reducing disaster risk and in post-disaster relief and recovery (Storlazzi et al., 2019). Without immediate, drastic action to reduce our reliance on fossil fuels and the associated carbon emissions, the future of our species and planet is in peril. To solve an issue of this magnitude will take individual, community, public-, and private-sector action. There must be a significant increase in engagement, support, and action for climate solutions and policy.

Our hope is that researchers realize traditional modes of science dissemination will not be sufficient to solve these environmental issues. By better marrying science and society through community engagement and citizen science, practitioners can both further their research and findings while simultaneously empowering communities to act as champions on the subject (Brossard et al., 2005; Jordan et al., 2011; Crall et al., 2013). Research is conducted to produce knowledge and enact change, but that change is not feasible unless there is measurable public support, participation, and action. The sciences are becoming increasingly isolated from the general public creating a disconnect and even a distrust, but citizen science can act as a powerful tool to build trust and democratize science (Bela et al., 2016). To bring science and society closer is creating a "scientific citizenship" where individuals are more engaged in environmental issues leading to decision-making, ownership, and action (Conrad and Hilchey, 2011; Dickinson et al., 2012; Jackson et al., 2015). Scientists can no longer rely on knowledge discovery and dissemination alone to create change. They must roll up their sleeves and co-create change with the communities who have an equal amount at stake. Rescue a Reef was designed to do just that: advance coral conservation, restoration, and stewardship through community education, outreach, and citizen science activities.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

DH, MK, and DL contributed to the conception and design of the study. DH and MK organized the database. MK performed the statistical analysis and created the visualizations. DH wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1250464/full#supplementary-material

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Rethinking disaster risk for ecological risk assessment

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While disaster events are consequential, they are rare. Ecological risk assessment processes tend to estimate risk through an "expected value" lens that focuses on the most probable events, which can drastically underappreciate the importance of rare events. Here, we show that expected value and average risk-based calculations underappreciate disaster events through questionable assumptions about equally weighing high probability low impact events with low probability high impact events, and in modeling probability as a chance among an ensemble of possible futures when many contexts of ecological risk assessment are focused on a single entity over time. We propose an update to ecological risk assessment that is specifically inclusive of disaster risk potential by adopting analytical processes that estimate the maximum hazard or impact that might be experienced in the future, borrowing from the practice of modeling "Value at Risk" in financial risk contexts. We show how this approach can be adopted in a variety of data contexts, including situations where no quantitative data is available and risk assessment is based on expert judgement, which is common for ecological risk assessment. Increased exposure to environmental variation requires assessment tools to better prepare for, mitigate, and respond to disasters.

KEYWORDS

ecological risk assessment, disasters, compound events, extreme values, repeat exposure, hazard

1 Introduction

Many environmental and development disasters such as floods, oil spills, droughts, heatwaves, landslides, and dam breaches have caused tremendous financial losses, displacements of millions of people, and devastated natural ecosystems and species (Frölicher and Laufkötter, 2018; IPCC, 2022a), but were often predicted to be low-risk events (Bull-Kamanga et al., 2003; Garcia et al., 2017; Ide et al., 2020; IPCC, 2021; IPCC, 2022a; IPCC, 2022b). There has been increased attention placed on rare events across disciplines including finance (Beamish and Hasse, 2022), conflict studies (Ide et al., 2020), public health (Mishra, 2020), and environmental management (Garcia et al., 2017). Intellectually, this turn to thinking specifically towards extreme events can be traced in part to ideas of "Black Swans" – unexpected and highly consequential events that disproportionately characterize systems and are very hard to predict – proposed and popularized by Taleb (2007).

Environmental and development disasters are the product of environmental hazards capable of catastrophic impact (whether from the biophysical environment or human activities) and a human or valued natural system that is exposed and vulnerable to the hazard (Aven, 2010; Sajid et al., 2020; IPCC, 2022a). Disaster hazards have highly consequential effects across a range of topics relevant to environmental management and sustainable development including wildlife disease (Beauvais et al., 2019), dam breaches (Jakob et al., 2016), glacial calving and coastal erosion (Overland, 2021), flooding (also due to climate change) and coastal development (Tsoukala et al., 2016), wildfire (Taylor et al., 2013), oil and gas spills (Afenyo et al., 2020; Sajid et al., 2020) and mining (Yang et al., 2021). Indeed, rare events and natural disasters have been recognized as contributing to species declines and extinctions (Penn and Deutsch, 2022), and development disasters (such as oil spills and mine tailings releases) have contributed to environmental devastation and severe social disruption in many contexts (Garcia et al., 2017). Currently, interest in "compound events" (where a combination of processes leads to a significant impact event, like a heatwave combined with a drought event) in climate change studies also recognizes the importance of understanding rare events for risk management (Zscheischler et al., 2018; Gruber et al., 2021). Disasters pose disproportionate risks to ecosystem services, and some studies trying to track impacts on ecosystem services have attempted to pay special attention to disasters as they impact ecosystem services (Singh et al., 2017a; Singh et al., 2020). Conversely, the ability of natural systems to protect against disasters is an ecosystem service, and managing ecosystems as nature-based solutions promises to protect against some disasters (such as floods), but evaluating the efficacy of nature-based solutions often depends on adequately estimating the magnitude of impacts (Kumar et al., 2021). Despite increased attention to disasters and rare events, many formal risk assessment processes neglect these rare, consequential events.

Risk is often defined as the product of the probability of an event and its associated consequences (Aven, 2010). By multiplying consequences by their probability, risk is often calculated as the "expected value" of something unfavorable or harmful occurring. Risk analysis, sometimes referred to as risk assessment, aims to estimate the probabilities of adverse impact events occurrences and the quantification of associated damages. Because risk is inherently future-oriented, risk assessment is an anticipatory tool for planning and is often employed in environmental impact assessment and other tools for environmental protection and sustainability (Bull-Kamanga et al., 2003; Aven, 2010; Mishra, 2020). The expected value risk model is pervasive in environmental management and science, from environmental impact assessments of individual projects to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022a).

Using expected value to model risk in rare events can be misleading (Haimes, 2005; Verma and Verter, 2007; Shaw, 2016; Baillon et al., 2018). This common formulation for risk can equate the risks of two events: one having a large likelihood and low consequence and another with low likelihood and high consequence. Both types of situations are calculated as being equivalently "risky" according to an expected value model, but here we argue that there are important cases where the latter cases require special consideration and tools of analysis.

Existing environmental risk assessment (ERA) techniques and subsequent environmental policies are often based on the hypothesis that "rare events are rare," dismissing events with low chances as posing little threat. Technically speaking, this assumption indicates that the "tail" of the probability distribution rapidly approaches zero and relatively little weight is given to extreme risks (Farber, 2010). While the expectation of risk based on its probability is low, the consequences can be very influential if the event materializes. For example, the risk of the sudden release of mine tailings waste into the deep sea has a very small chance of occurrence in any single event, but its harmful impacts could last years to centuries, and may be irreversible (Hughes et al., 2015; Miller et al., 2018) – causing significant damage to the environment and ecosystem. Mine tailings release is a repeat exposure problem – which means it is not something that might occur at one point in time during the lifespan of a mine operation (and therefore low probability when spread over time), but rather there is the same probability throughout the lifespan of the mine operation (or greater, if stability decays over time) and thus total probability is higher due to repeated risk of occurrence. While the occurrence probability for tail events is low in any given time, their repeated exposure over a long timescale increases the chances of catastrophic outcomes.

An additional problem with expected value models is that they can provide the appearance that many small risk events are equivalent to a single large one. This idea is promoted in publications to rank and evaluate risk events together, including the IPCC (IPCC, 2012; Roux et al., 2022). However, a single catastrophic event can overwhelm an ecosystem's ability to recover, while a series of small impacts may be recoverable between events (Garcia et al., 2017; Mishra, 2020). Events with low occurrence probability (fewer chances to occur) but high consequences (catastrophic outcomes) may be of primary interest to environmental management once they occur, but may be classified as "low risk" in anticipatory decision-making (Farber, 2010). While the occurrence probability for tail events is low at any given time, their repeated exposure over a long timescale increases the chances of catastrophic outcomes. Here, we show how expected value models can underappreciate the risk of rare events and propose a framework for ERA that can better account for rare but highly consequential events.

2 Rethinking consequence and probability for repeat exposure events in risk assessment

The expected value risk model suffers two issues as they relate to disasters in ERA. The first issue is the fact that the model is symmetric with its treatment of the factors that contribute to a risk "value". In other words, these models can treat proportionally low consequence yet high probability risks equivalently with proportionally high consequence yet low probability risks. However, as has been noted in the project management literature, high impact events intuitively and analytically should be given greater concern than low impact events (Haimes, 2005). Suppose that a particular risk value "r" has a probability "P" of occurrence and can incur a consequence "C" if it does occur. Using calculations of risk based on the Bernoulli distribution of event probability combined with a consequence, greater risk consequence carries greater variance of risk and therefore a requires a greater contingency to manage it (Williams, 1996). Mathematically this is represented as,

$$\mu_r = P \times C$$

$$\sigma_r^2 = P(1 - P)C^2 = \mu_r(C - \mu_r)$$

Where "μ_r" is the mean risk and "σ^2_r" is the variance of risk. This equation shows that for a constant value of "μ_r", larger values of "C" equate to larger variance in risk.

Relatedly, the expected value of risk model neglects the presence of non-linear and "tipping-point" threshold impacts. The literature on climate change and ecosystem management highlights a diverse array of tipping-point examples, whereby, for example, ecosystems can change from one state to another due to some environmental threshold being crossed as a result of an impact, and our certainty about such events tends to be low (Dakos et al., 2019; Martin et al., 2020; Armstrong McKay et al., 2022). Moreover, as a non-linear change results in a qualitatively different ecosystem, the assumption of multiple, small quantitative changes being equivalent to a single large qualitative change is unlikely to hold.

The second issue with the expected value approach in ERA is in the treatment of probability. Probability has different relevance when thinking about the likelihood of an ensemble of cases where a proportion of cases will experience an event at a point in time, versus whether a single system will be exposed to an event over time. In the first case, a rare event is rare, no matter how extreme the consequence of an event is and will affect a small proportion of cases at a given point in time. In the second case, exposure to a rare event is repeated over time, and the probability of facing it over the duration of the lifespan of the system is often different (and far greater) than the probability of an ensemble of cases facing an event. The path dependency of risk (where experiencing an impact can have drastically different consequences if faced at the beginning of a time series versus at the end, or if facing multiple impacts at shorter intervals versus longer) means that evaluating risk by its expected consequence is misleading. Moreover, the impact of disasters is not mediated once they manifest; put another way, in path dependent systems once a consequence is experienced the probability that the consequence may have occurred no longer matters (Hopkins, 2016). The expected value model of risk equates many small but frequent impacts with a single large but infrequent impact, but the two do not express the same concern, especially where the large impact is irreversible. For example, a tailings dam at the Córrego do Feijão iron ore mine near Brumadinho, Brazil burst in 2019, causing a mudslide that killed 232 people. The dam likely failed because of time-dependent decay processes affecting its stability. Prior to collapse, the dam was rated as a small structure with a low risk of high damage, based on short-term monitoring and laboratory experiments which failed to account for long-term decay (Santamarina et al., 2019; Primo et al., 2021). That is, the probability of dam burst increased as time passed, meaning the likelihood of disaster was unappreciated. Perhaps more importantly, once the impact was realized, the "low risk" assessment of disaster and risk management led to distrust in institutions responsible for risk management (Primo et al., 2021).

Research on ecological communities has shown that changes in the variation in some hazards may pose a greater threat than changes in mean hazard effects (such as warming effects) because of exposure to extremes (Vasseur et al., 2014). Many ecological communities also respond non-linearly to hazards and disturbances, so that ecological processes at average conditions are rarely equal to the average ecological processes across a range of conditions (a phenomenon known as Jensen's inequality, Denny, 2017). Therefore, where ecological systems are more vulnerable to more severe hazards (such as toxicological thresholds and thermal effects), considering the consequence of the average or most likely hazard may underestimate the impact (Denny, 2017; Bernhardt et al., 2018). Social-ecological systems are subject to path-dependence (such as whether a 1 in 200-year rain event occurs before or after the accumulation of toxins in a mine tailings pond designed with retaining walls to withstand a 1 in 100-year rain event), face nonstationary processes contributing to extreme events (where processes change in space and/or time, such as through climate change), and subject to non-linear changes where environments can change qualitatively (not just quantitatively) into new states (Leonard et al., 2014; Dakos et al., 2019). Single events can have radical consequences and one cannot understand the system by assessing just the weighted average of possibilities. Therefore, there is a need to develop a risk assessment framework that could reflect these dynamics.

3 Lessons from other fields of study to address low-probability high-consequence events

In economics, expected utility theory has been recently criticized for its treatment of probability. Ole Peters has coined the term "ergodicity economics" to differentiate the use of probability in dynamic contexts, where economic models are interested in understanding consequences for a single person making a series of choices over time, from static contexts where probability is formulated for understanding consequences among an ensemble of people in a given point of time (Peters, 2019). Peters' critique is inspired by the idea of "ergodicity" from equilibrium statistical mechanics, which is a condition where the state of a particle over time is equivalent to the state of a particle across all possible spaces (Palmer, 1982). This assumption accurately describes the thermodynamic behavior of gases. In economics, Peters calls economic systems ergodic where an object's time-averaged utility equals the expected value of utility. However, because economic systems rarely have economic agents exposed to all possible states (because path dependencies affect their economic prospects, and the number of possibilities that an economic agent can experience over their life rarely if ever meets the total number of possibilities that could come about), the ergodic condition is rarely if ever met. In situations where the ergodic condition is not met, an expected value model is inadequate because its treatment of probability assumes that an agent will experience all possible states. The lessons from economics can inform ERA because for environmental assessment, individual ecosystem components rarely experience all possible states over time – that is, ecosystem components are often not exposed to all possibilities, partly because a disaster event can permanently change ecosystems before it has experienced all possible events. An expected value model of risk assumes ecosystem components will experience all conditions, and so the expected value of risk is inadequate.

There are criticisms of ergodicity economics, notably that economists have already been able to address utility dynamically (Doctor et al., 2020), though these alternative approaches also highlight the limitations of static expected value models. In addition, other authors have proposed the "dismal theorem" of economics modifying expected value formulations (Weitzman, 2009). Using the dismal theorem, the declining probability of disaster (which declines polynomially) is outstripped by the increasing impact of disaster (which increases exponentially) (Weitzman, 2009). While the technical aspects of the dismal theorem have been challenged for its critiques of standard economic analysis, even the critiques acknowledge the legitimacy of the caution that the dismal theorem raises about the underlying distribution and treatment of extreme risks over time (Nordhaus, 2009). Again, the lessons from economics for ERA is to pay special attention to rare but consequential events.

In science and technology studies, a rich literature is developing on "manufactured risk", whereby efforts to deepen and extend natural resource development into new frontier zones significantly raise the risk of disasters, especially in variable environments (Knowles, 2012; Fortun et al., 2017). The empirical material for this work involves careful analysis of well-known and documented disasters including the Deepwater Horizon blowout (Watts, 2016), Hurricane Katrina (Frickel and Vincent, 2007; Hilgartner, 2007), the Fukushima nuclear power disaster (Pritchard, 2012) and the Bhopal chemical disaster (Lerner, 2017), amongst many other socio-ecological disasters. These analyses across cases reveal a number of key insights leading to the disaster including the problem of weaker state regulatory systems, the financialization of resource development and intense corporate competition (Watts, 2016; Lerner, 2017). The manufactured risk literature is valuable to ERA in arguing that disasters should not be seen as unexpected or exceptional, but are instead built into new and existing technological systems for resource extraction and development, and are partly a consequence of human decisions and infrastructure (Knowles, 2014).

Climate research is documenting that climate change is creating more variable or extreme environments in many places, which can increase disaster potential (Hallegatte, 2016). For example, extreme ocean events such as marine heatwaves have strongly increased in frequency over the last few decades and are projected to strongly increase under further global warming (Frölicher et al., 2018; Oliver et al., 2018). Critical thresholds for some ecosystems (e.g. kelp forests or coral reefs) will be reached at relatively low levels of future global warming (Collins et al., 2019). In addition, the IPCC AR6 WGII report concluded that widespread, pervasive impacts to people, ecosystems, settlements and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes, heavy precipitation events and drought and fire weather events (IPCC, 2022a). As a result, millions of people have been exposed to food insecurity and reduced water security, and extreme heat events on land have resulted in human mortality and morbidity.

Climate studies are also increasingly concerned with understanding compound disaster events, and have proposed methods to investigate them. The use of influence diagrams has been proposed to understand the conditional dependencies of risk when they are consequences of compound events (e.g. a heat-drought event: Ridder et al., 2022; or a marine heatwaves-high acidity event in the ocean: Burger et al., 2022), and usually studied in climate disaster contexts (Leonard et al., 2014). In a similar way, influence diagrams can be usefully employed to model the causal (or even statistically associated) processes that lead to extreme events for ERA. Influence diagrams are a generalization of Bayesian networks, and can graphically be used to explore the relationship between variables in a system (Leonard et al., 2014). While climate studies have mostly proposed the study of compound events when considering climate disasters, we propose that the methods can also be used to understand how climate and other stressors contribute to natural and industrial disasters.

In statistics, extreme value theory (EVT) has been widely used to model rare events, especially in natural sciences and engineering (Coles et al., 2001; Ahmad et al., 2019; Owusu-Ansah et al., 2019). EVT has also been used in dealing with rare events problems in ERA, such as air quality analysis (Sharma et al., 2012), flood analysis (Morrison and Smith, 2002) and system reliability studies (Grigoriu and Samorodnitsky, 2014). The focus of EVT is not to study the central tendency (data around the central or mean value) of the data; instead, the focus has been on the tail sides of the probability distribution. EVT aims to approximate mathematical formulations for tail probability using either two or three parameters. Classical EVT represents the probability tail using scale and location parameters, while generalized EVT uses a third exponent parameter (Chryssolouris et al., 1994). Extreme value distribution parameters are estimated assuming that the data's original distribution is unknown, and that parameter estimation is not performed on the whole population of data but rather the population of the extrema (maximum or minimum) (Lazoglou and Anagnostopoulou, 2017). Therefore EVT quantifies the probabilistic tail behavior (McNeil and Frey, 2000; Fernández, 2003). EVT provides appropriate tools for ERA to quantify extreme risk where expected value models do not.

4 An illustration of the role of extreme events in environmental risk

To explore risk assessment and extreme events, we model a wildlife population at carrying capacity (K=10,000 individuals), under logistic growth dynamics and subject to varying impacts from development. We simulate two scenarios using stochastic model where both growth rate and annual impact on the population are stochastic. In the first scenario, impact magnitude follows a normal distribution, so extreme events have truly negligible probabilities. In the second scenario, extreme events are rare but still plausible (modeled using a fat-tailed Cauchy distribution that includes the rare possibility for catastrophe whereby the full population of 10,000 individuals may die at once). Both scenarios show continuous exposure to impact, but only the second has continuous exposure to potential disasters. According to the expected value of risk, the risk of the development is a mortality of 123 individuals in each scenario, which should easily be offset by the mean implicit birth rate in the model of 0.2 and a starting population of 10,000.

When modeling this expected value using the normal distribution, we indeed show that risk is low (the population maintains a healthy population over 100 years across all 1000 simulations (Figure 1A). However, over 1000 simulations of 100 years of the model, where the population is exposed to the potential for disaster, we find that in approximately 30% of cases the population experiences impacts that reduce it to under 75% of carrying capacity at some time during the 100 years (often taking decades to recover – if the population does fully recover). Of this subset of cases where catastrophes are experienced, approximately 40% of simulations see the population collapse completely (Figure 1B). Within a simulation where catastrophic impacts are realized, the expected value of risk severely underestimates the realized effects. Crucially, a single catastrophic event can counteract years to a century of population growth. In other cases, sequential catastrophic events can collapse a population (that is, multiple sequential years of substantial impact can compound and fully depress the population). The expected value model of risk would neglect the importance of the rare catastrophic event or the sequential, compound event.

5 A proposal for extreme event ecological risk assessment

To better assess risk that is reflective of the importance of low-probability high-consequence events, we propose a conceptual framework for their inclusion in ERA (Figure 2). The first step in the proposed conceptual framework is identifying and assessing the

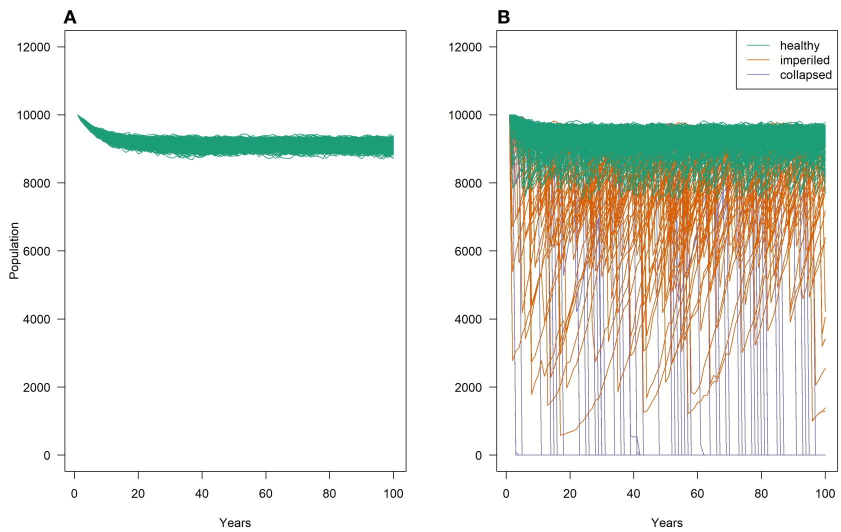


FIGURE 1
One thousand stochastic simulations of a wildlife population under logistic growth dynamics and facing repeat exposure of catastrophic impacts. An expected value model of risk would estimate risk at 123 individuals per year, which represents approximately 1% of the starting population, which should be offset by the intrinsic growth rate of 20%. Under dynamics where this "expected value" trulv,y represents impacts year to year, the risk of development is indeed low **(A)**. However, simulations allowing for repeat exposure and path dependence where there are low probabilities of catastrophic effects in any given year show that in approximately 30% of cases, the population loses a quarter of its population during the time span, and in 8% of cases, the population collapses **(B)**. In these simulations, "healthy" runs never had the population dip below 75% of the carrying capacity, "imperiled" runs had populations dip below 75% of their carrying capacity at some point during the time span, and "collapsed" runs had the entire population collapse.

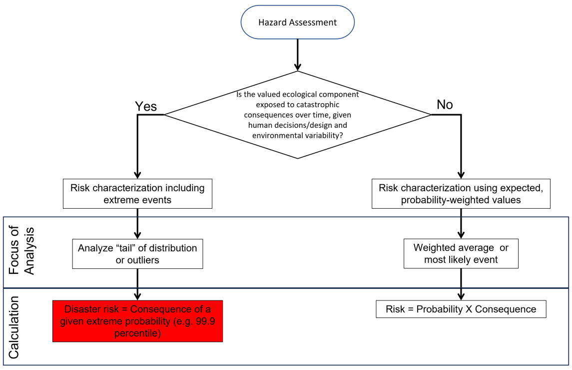


FIGURE 2
Theoretical framework for environmental risk assessment including disaster potential.

hazards. This step systematically identifies and assesses the potential sources and the type of harm to the environment. As a core element to define environmental risk problems, this step establishes the scope of the study and specifies what needs to be protected. This step is similar to typical ERA; however, rather than moving immediately to quantifying the expected value of risk from the hazard or identifying what level of risk is most likely, assessment should consider whether hazards include extreme impacts or disasters.

In assessing hazards inclusive of extreme events, we suggest the following criteria. First, there should be a deliberate search for hazards that have catastrophic consequences. Second, if there are hazards that present possibilities for low-probability yet high-consequence impacts, it should be determined if these are events that will only occur once or if environments and communities face repeat or continuous exposure to them. Third, we argue that hazards need to be considered in a larger social-ecological context, including both human decisions that can introduce disaster hazards (such as neglecting maintenance that can increase the chances of oil spills) and environmental variability (especially climatic conditions) that can introduce or increase the probability for disasters.

Our proposal is to use influence diagrams to model a system and explore the human decisions and environmental variables that can introduce or increase the probability of disasters. Where these situations are present, we propose that risk characterization include an explicit quantification of extreme events.

After hazard identification and assessment, risk characterization is the next step. Where extreme events are possible, we propose that risk characterization for that hazard should focus on the extreme value of risk rather than an expected value of risk. Such an approach mirrors the practice of Value at Risk (VaR) used within financial risk to estimate the extent of financial losses to an organization within a specific time period under a given confidence level (Duffie and Pan, 1997). VaR approaches are often used to assess the extent of risk exposure for banks and other lenders toward ventures they fund. We think ERA often operates in an analog case, where government regulators must determine if a development project poses too much risk to the environment and public interest. In both cases, there is an assessment of risk to protect the interests of a benefactor (the lenders or public agency) from potential harm while furthering the interest of a recipient (a business or a developer).

Determining what counts as low-probability high-impact, extreme risks, or disasters is an important consideration (Aven, 2012). While there are no hard rules, there are some substantive criteria around the "consequence" of risk that should be considered, and some analytical tools that can help. First, risk events should be judged in accordance to the severity of their consequence in context, absent of their probability. Risk events that could have catastrophic impacts should be given this special treatment, especially if they are events that communities and ecosystems will be exposed to repeatedly or continuously. As discussed earlier, catastrophic risk can be from natural catastrophic events and it could be a product of manufactured conditions or human decisions.

When identifying high-consequence events, it is important to identify them inclusive of the most likely events, the presence of outliers, and rare events (extreme outliers). The importance of evaluating extreme outliers (even potential ones) in the tail of distributions should not be neglected because failing to include them can lead to a substantial underappreciation of risk (Devore, 2008; Weisent et al., 2014).

While we outline a process to identify extreme risk, any risk assessment should feed into environmental decisions. Identifying the scale of extreme risks can help determine the potential scale of loss that decision-makers will need to be ready for. In contexts where the ERA is used to determine whether and what kinds of development to pursue (such as in Environmental Impact Assessment), extreme risk evaluations can help determine which options pose less disaster risk. In contexts where decision-makers are determining mitigation plans, we warn that repeat exposure problems may mean that efforts to reduce exposure may do less to limit risk than managers intend. In some cases, exposure to disaster can be eliminated (such as if plans allow for vulnerable ecosystem components to be separated from a potential hazard, or if processes that contribute to disaster risk were eliminated), which the influence diagram used in our approach can help determine. However, in cases where exposure to disasters cannot be eliminated, our analysis can instead indicate the scale of impact that managers should prepare post-disaster response measures for.

6 Case study of the proposed framework

In this case study, we used a past oil spill example of the Gulf of Mexico (GOM) to showcase and validate the operationalization of the proposed framework. We study the feasibility of using our framework for extreme oil spills by comparing it against an assessment using expected value models of risk. The GOM's Outer Continental Shelf (OCS) is a major source of oil production in the United States. The Minerals Management Service (MMS) of the United States Department of the Interior was responsible for its operations. The past oil spill database

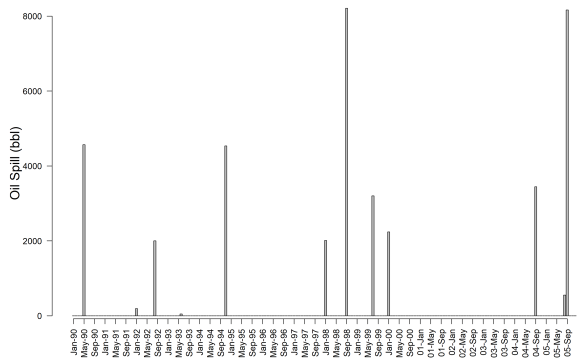


FIGURE 3
Gulf of Mexico 15 years Pipeline Oil Spills from May 1990 to September 2005.

maintained by MMS has been extensively used for statistical analysis to predict the volume of future oil spills in GOM (Us, 2006).

From 1990 to 2005, GOM experienced a series of oil spills (Figure 3 – see Table S1 and Eschenbach et al., 2010 for data). The causes of the oil spills can be categorized as human-caused (which include operational and mechanical failures) and natural disasters (such as hurricanes). Existing models for ERA for oil spills in this duration are often based on using "average" measurements of the oil spill. However, two rare events triggered oil spill disasters within the span of seven years, while the ERA employed predicted such events so rare as to be low risk. As shown in Figure 3 these two rare events caused oil spills much higher than spills due to standard operational and mechanical failures. The first rare event occurred on September 29, 1998, due to Hurricane Georges and caused an oil spill of 8,212 bbl. The second rare event occurred on September 24, 2005, and it was due to Hurricane Rita which caused an oil spill of 8,162 bbl. Both hurricanes caused exceptional damage to oil and gas structures and drove significant ecological losses (Eschenbach et al., 2010). Hurricane Rita damaged 103 platforms and extensively damaged 33 drilling rigs and is known as the 4^{th} most intense Atlantic hurricane in history.

To compare the efficacy of our proposed approach to quantify the risk of extreme events compared to an approach fitting an expected value model, we first note that our hazard identification shows climate change as increasing the probability of oil spills, triggering our risk characterization to quantify extreme events (Figure 4). We performed our analysis on the oil spill data by excluding the September 24, 2005, event (the extreme spill of 8,162 bbl) and then used it to validate our analysis. First, we quantified the expected value of spills, as the weighted sum of the products of probability and magnitudes of spills of given sizes. Mathematically,

$$\text{Expected value of risk} = E(x) = \sum xi \times P(xi)$$

where xi indicates the value of the random variable (spill size) and P(xi) is the probability of the random variable occurrence. For comparability across approaches, we fit the same distribution to the data in each case. We fit a Weibull distribution to the data (a flexible continuous probability distribution that can accommodate many datasets, including non-negative skewed data, and which we determined to fit the data better than other probability distributions). focused on extreme events). We calculated the expected value of a spill risk to be 2730 bbl of oil. In fact, calculating the product of spill magnitude by probability (the expected value), a spill of 2766 bbl contributes the most risk to the expected value calculation, and is weighted 2.4 times the risk of the extreme spill of 8162 bbl.

To compare these results with an analysis inclusive of catastrophic risks, we estimate the extreme value of spills from the oil spill data. Our results show that at a 99 percent confidence

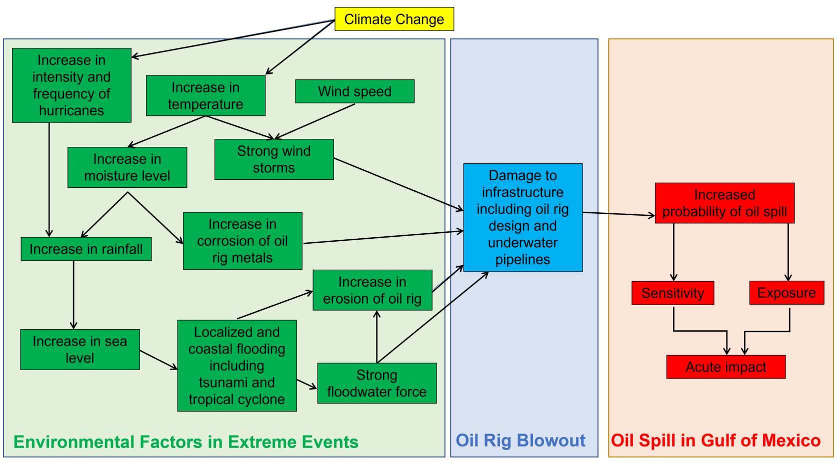


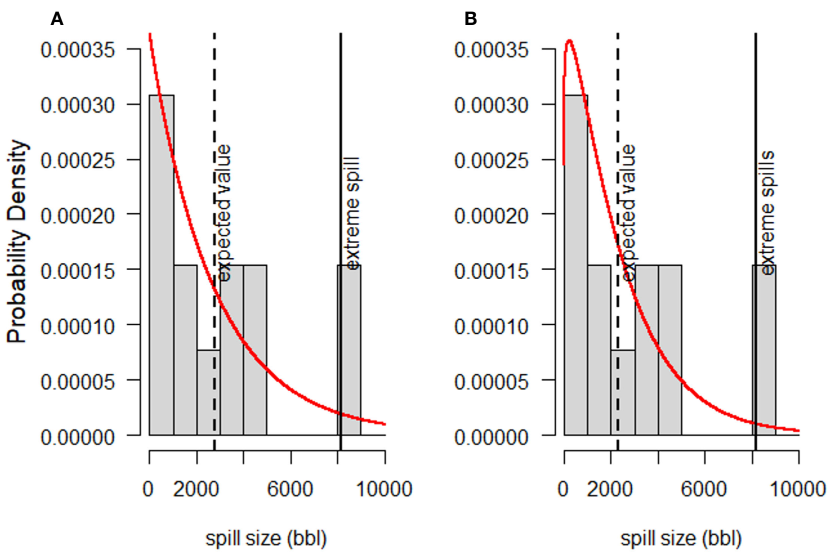
FIGURE 4
Influence diagram of the risk factors contributing to oil spill risk. Climate change is understood to increase spill risk and spill magnitude (based on Eschenbach et al., 2010).

level, an oil spill can be 12803 bbl or more. In fact, even excluding both historic extreme spills (1998, 2005), the 99 percent confidence level of how big an oil spill could be 9398 bbl (Figure 5). These results adequately capture the experienced extreme oil spills, including the 2005 spill of 8,162 bbl. Hence, comparing the results using the expected value of risk against our proposed framework of including extreme events supports our argument that tail risk assessment captures or comes closer to the size of a near actual oil spill and the predictions of the disasters should not be solely based on weighing the consequences and their probabilities. Therefore, tail risk assessment is more reflective of the reality than using the expected value for rare events. The inclusion of tail risk assessment in assessing oil spill risk could have helped the company to estimate potential oil spills due to rare events such as that of September 24, 2005, event.

Risk communicators could take this analysis to decision-makers as "worst-case" scenarios that should be prepared for. Given that climate impacts (through storm events) could increase the chances for large-scale spills, and these impacts may be hard or impossible to fully mitigate, disaster response planning may be a more responsible decision than a mitigation plan focused on reducing the probability of disaster (especially where the disaster cannot be fully avoided). This analysis could help inform decisions regarding disaster response – it could allow the MMS to prepare to respond to spills multiple times larger than what an expected value model would predict. Importantly, well-resourced governance structures allowing for rapid response plans are critical for reducing the severity of oil spills (Chang et al., 2014; Sajid et al., 2020), and being ready for extreme spills can help contain their effects better than being ready for "expected" spills.

7 Disaster risk assessment with data paucity

In practice, there is often a severe paucity of data to conduct formal probabilistic assessments of risk (Singh et al., 2017b). This is particularly true for emerging industries where there is little or no precedence (Singh et al., 2020). In such cases, risk assessment often relies on risk matrices. These matrices are qualitative or semi-quantitative tools to assess risk based on the likelihood and consequence of events and guide analysts to an overall "risk score" (Anthony Cox, 2008; Thomas et al., 2014). Risk matrices provide a framework to rate risk based on scorings of likelihood and consequence. In a typical qualitative risk assessment, a risk matrix will contain tiers of high, medium, and low values to approximate both the risk likelihood and impact, but some instances may have more tiers of likelihood and consequence (Figure 6). These matrices are often constructed with symmetry, so low-probability high-consequence events and high-probability low-consequence events receive the same scoring and follow similar logic to expected value models of risk, where the likelihood of impact regulates the final risk score (Figure 6A).



Rare Event Probability	Excluding 2005 extreme event	Excluding both extreme event
1/20 event (95% confidence)	8317 bbl	6323 bbl
1/100 event (99% confidence)	12803 bbl	9398 bbl
1/1000 event (99.9% confidence)	19230 bbl	13657 bbl

FIGURE 5
Histograms of the historic oil spills in the Gulf of Mexico. Red curves represent fitted Weibull distributions for a case where the 2005 extreme spill is excluded from the model fit **(A)**, and where both extreme spills from 1998 and 2005 are excluded from the model fit **(B)**. Broken vertical lines show the expected value of risk given the model fit in each case, and the solid vertical lines show the extreme spills of 1998 and 2005. The table below shows the modeled rare events given different levels of confidence for each modeled distribution, showing that a focus on the tails of the distribution rather than the most probable better predicts the extreme spills experienced.

A

Likelihood	High	Medium risk	High risk	Very high risk
	Medium	Low risk	Medium risk	High risk
	Low	Very low risk	Low risk	Medium risk
		Low	Medium	High
		Consequence		

B

Likelihood	High	Medium risk	High risk	Very high risk
	Medium	Low risk	Medium risk	Very high risk
	Low	Very low risk	Low risk	Very high risk
		Low	Medium	High
		Consequence		

FIGURE 6
Examples of a three-tiered risk matrix. A typical risk matrix is symmetric, where tiers of likelihood and consequence can influence the resulting risk judgement **(A)**. We suggest a modified risk matrix where disasters may occur under repeat exposure, with an asymmetric risk scoring so likelihood cannot influence high consequence outcomes **(B)**.

The applications of these matrices range from environmental impact assessments of individual development projects to government risk assessment guidelines (Anthony Cox, 2008; Thomas et al., 2014). The IPCC AR5 and AR6 WGII reports also employ the logic of risk matrices and model "tolerable *vs.* intolerable risk" *via* a symmetric consideration of the intensity and frequency of impacts (IPCC, 2014; IPCC, 2022a).

In situations where rare events with disaster consequences can occur in repeat exposure settings, we recommend risk matrices follow an asymmetric structure, so that all cases of high consequence be labeled as "high risk", regardless of the probability (Figure 6B)

8 Conclusions and future directions

By modeling risk as an ensemble of outcomes at a point in time, the conventional expected value model of environmental risk inadequately captures threats posed to a single entity over time. Disasters are not moderated by the low probability of occurrence when exposure to them is continuous. By providing a decision framework to consider disaster risk in parallel with more common risks, we propose an update to how ERA could be conducted. With greater emphasis placed on low-probability high-impact events, we believe better practices can be implemented to prepare for, mitigate, and respond to disaster occurrence. The implications of this also affect how analysis informs risk management strategies, including assessments of risk equivalences, which are assessments aimed at informing management in order to maintain comparable risk given different management decisions (Roux et al., 2022). If there are risks to the environment that include repeat exposure of potential catastrophe, we argue that a risk equivalency approach based on expected value models cannot meaningfully compare between low-consequence and high-consequence risks.

Further, common risk management approaches to decrease the probability of exposure to impacts may only be reliable in contexts of repeat exposure catastrophe where these high consequence risks are eliminated and not simply less likely at any given time. Importantly, understanding the scope and magnitude of disasters are important to not only evaluate how ecosystem services may be impacted – so response planning can be adequately done – but also to design and evaluate environmental management to withstand and recover from disasters. Designing nature-based solutions to climate impacts depends on adequately estimating and modeling disasters, and our proposal attempts to better quantify disaster risk.

We suspect that our proposed approach can also aid in evaluating compounding or cascading disaster events. By incorporating influence diagrams to assess the association between events, our approach should be able to connect the possibility of cascading disaster events, including when natural disaster events can cascade into industrial disaster events (such as when an extreme weather event leads to an oil spill or tailings release). However, because our approach relies on using extreme value theory, which fits probability distributions around past events to evaluate tails of the distribution, our approach may still be inadequate to address the magnitude of impacts of unprecedented events (which may be the case with some cascading disasters). There may be more opportunities to combine our approach with disaster simulation models, to first build a simulation database and then conduct an analysis of extreme values.

Our suggested approach is intended to be simultaneously rigorous but flexible to use, which can be employed and recommended in individual environmental impact assessments to large regional and global scale analysis of risk, from situations allowing for complex and data-driven probabilistic assessments to data-poor contexts. We hope that recent and renewed attention to disasters will generate efforts to understand their risk with new tools that do not discount the threats they pose.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

GS and ZS, FK, and CM conceived the paper. Analysis and figures were conducted and produced by GS and ZS. GS, ZS, FK, CM, JB, and

TF provided examples and perspectives on the topic from their relevant disciplines, and all authors contributed to the writing and editing of the paper. All authors approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1249567/full#supplementary-material

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The final ecosystem goods and services Voltron: the power of tools together

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Environmental decision-making benefits from considering ecosystem services to ensure that aspects of the environment that people rely upon are fully evaluated. By focusing consideration of ecosystem services on final ecosystem goods and services (FEGS), the aspects of the environment directly enjoyed, used, or consumed by humans, these analyses can be more streamlined and effective. The U.S. Environmental Protection Agency has developed a set of tools to facilitate this consideration. The central feature of FEGS is that ecosystems are viewed through the diverse ways people directly benefit from them. The National Ecosystem Services Classification System (NESCS) Plus provides a framework for describing and identifying FEGS consistently. The standardization made available by NESCS Plus allows other tools and databases to interact using the NESCS Plus architecture and taxonomy, providing diverse insights for decision makers. Here, we examine the synergy of using the following four tools together: (1) the FEGS Scoping Tool; (2) the FEGS Metrics Report; (3) the EnviroAtlas; and (4) the EcoService Models Library. The FEGS Scoping Tool helps users determine what ecosystem services are relevant to a decision by harnessing FEGS understanding to enable communities to identify the relative importance of beneficiaries relevant to a decision and biophysical aspects of the environment of direct relevance to those beneficiaries. The FEGS Metrics Report can guide which metrics to monitor or model to represent those priority services. The EnviroAtlas, a powerful tool containing geospatial data and other resources related to ecosystem services, chemical and non-chemical stressors, and human health, and the EcoService Models Library, a database of ecosystem models, are two tools that support users in mapping and modeling endpoints relevant to priority services. While each of these tools is valuable on its own, together, they provide a powerful approach to easily incorporate and operationalize ecosystem services efforts into different parts of decision-making processes across different types of decisions. We illustrate how these integrated tools can be used together with a hypothetical example of a complex environmental management case study and the combined benefit of using the FEGS tools together.

KEYWORDS

decision support tools, community decision-making, stakeholder engagement, ecosystem services, final ecosystem goods and services

1 Introduction: ecosystem goods and services and final ecosystem goods and services

Humans are inextricably connected with the ecosystems in which we exist. Costanza et al. (1997) and the 2005 Millennium Ecosystem Assessment attempted to make this connection tangible through the concept of ecosystem goods and services (EGS)[1], defined as the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being. Acknowledging these connections in decision-making is critical for ensuring that the aspects of the environment that relate to the decision are comprehensively considered. This can be challenging, however, as connections between ecosystems and humans are complex, nonlinear, and dynamic (Costanza et al., 2017). First, there may be synergies or tradeoffs among services. Second, contributions to well-being vary spatially and temporally. For example, people who live in cities enjoy EGS that can be influenced by ecosystems far away. Third, the magnitude of societal welfare effects depends on interactions between the ecosystem services provided and manufactured, human, and social capital. For example, the recreational and aesthetic benefits of a park, lake, or beach depend on their accessibility through walkways, boat ramps, etc. These complexities are further amplified by difficulties communicating these connections within and outside scientific communities and environmental decision-making bodies.

To improve communications with these audiences and linkages with social analyses to make the concept of EGS more actionable for decision makers, the concept of final ecosystem goods and services (FEGS) was developed. Final EGS are defined as those "components of nature, *directly* enjoyed, consumed, or used to yield human wellbeing" (Boyd and Banzhaf, 2007). As such, they represent only the subset of EGS that contribute to well-being (note: understanding indirect or intermediate EGS underlying FEGS is crucial if we wish to understand, assess, or manage them). FEGS are identified by focusing on the distinct ways in which humans benefit from the environment. Analyses using this approach view ecosystems as systems of production in which biophysical features and conditions are combined to produce socially valuable environmental outcomes and are explicit about the myriad ways humans benefit from those outcomes. These two aspects of FEGS, explicit acknowledgment of *how* humans benefit and *what* they are benefiting from, are critical as they support well-defined connections between different aspects of the ecosystem and specific beneficial uses that they are supporting. Because of these connections, using a FEGS approach can be a particularly effective way of incorporating EGS into decision-making (DeWitt et al., 2020).

Over the years, many decision support tools have been developed to incorporate EGS into decision-making (Harwell et al., 2023; Newcomer-Johnson et al., in press). These tools can be used for different types of decisions and at different points in the decision-making process. All of these tools support decision makers in various ways but they discuss EGS differently, which means that using them in concert requires decision makers to make decisions about how the various definitions of EGS connect to one another. These tools are developed for decision makers with limited time and resources, the additional time required to learn multiple EGS classification systems and to develop crosswalks amongst them can be an obstacle to tool adoption. The U.S. Environmental Protection Agency (EPA) has developed a set of tools that address different decision maker needs and can be used at different points in the decision process but use the same EGS framework. The burden of tool adoption and the obstacles to tool accessibility can be reduced through the use of a consistent and comprehensive EGS framework that supports integration of these tools and facilitated the incorporation of multiple tools into a decision-making process. Here, we review the advantages and disadvantages of common EGS classification systems for the purpose of demonstrating the aspects of the National Ecosystem Services Classification System (NESCS) Plus that made it particularly useful for decision-making and for EPA tool developers. We describe the EPA tools using the NESCS Plus framework and the synergistic potential arising from tool integration. Finally, we also suggest that the utility of these tools will continue to increase as new tools use and existing tools adopt this same EGS framework.

2 Classification systems

The complex connections between environmental changes and human well-being can make deliberate and focused consideration of

1 Although formally goods and services are distinct, we follow the common convention and use "services" to refer to both.

ecosystem services challenging. Defining, measuring, quantifying, valuing, or accounting for EGS requires a collaborative effort among natural scientists and social scientists as environmental processes and functions produce potential EGS, and people, groups, or organizations enjoy, use, or consume EGS. This means that descriptions of EGS must be clearly defined in terms of the ecological context, the human benefit, and the connection(s) between them. Further complicating these descriptions is that the connections are often not linear, one-to-one relationships. A single environmental attribute may provide multiple benefits and a single benefit may rely upon multiple attributes. Therefore, a classification system provides an organizational framework to describe EGS consistently and comprehensively in efforts to assess, measure, quantify, map, model, or value the impacts of environmental changes. In general, classification systems offer the benefits of a unifying language, an understanding of how each category and its elements are related, improved identification of metrics, and improved knowledge transfer among research efforts (Finisdore et al., 2020).

Various ecosystem service classification systems have been developed to organize and clarify the wide-ranging kinds of ecosystem services, enabling discussions, (biophysical and economic) modeling, and welfare valuation. By making the link between ecosystem services and well-being explicit, decision makers have become more informed when implementing new policies (Ruckelshaus et al., 2015; Barton et al., 2018; Dunford et al., 2018). The most prominent classification systems[2] to date include the MEA, The Economics of Ecosystems and Biodiversity (TEEB) project, the Common International Classification of Ecosystem Services (CICES), and the National Ecosystem Services Classification System Plus (NESCS Plus) (see Finisdore et al., 2020 for more detail on these and other classification systems).

The MEA began in 2001 as an ecological project under the United Nations Environmental Programme (UNEP). It was established to help develop the knowledge base for improved environmental policy decision-making (Duraiappah et al., 2005). Ecosystem services are categorized into provisioning (e.g., food, water, timber, fiber), regulating (e.g., services affecting climate, flooding, disease, waste, and water quality), supporting (e.g., soil formation, photosynthesis, nutrient cycling), and cultural (e.g., recreational, aesthetic, and spiritual benefits) (Duraiappah et al., 2005). The MEA is a conceptual model of the interactions between biodiversity, EGS, well-being, and human drivers of change (e.g., population growth, technological advances, and lifestyle changes). In addition, it accounts for the spatial and temporal dimensions that influence these interactions. The advantage of this conceptual model is that it incorporates the full complexity of ecosystem services and their interactions with humans to assess welfare impacts. However, the MEA has several disadvantages. First, including supporting (or intermediate) services, which provide indirect societal welfare benefits by maintaining processes necessary for the other types of ecosystem services, can lead to double counting the economic value of a service (Fisher et al., 2009)[3]. Second, it does not differentiate either the uses or users of a service. Third, its delineation of provisioning service mixes ecosystem activity together with human activity making accounting and analysis imprecise. Despite its issues, the MEA has done much to boost awareness that protecting ecosystems (and maintaining their functioning and deliverability of services) is necessary to preserve peoples' well-being (Mulder et al., 2015). The classification systems described below, which attempt to address these issues, have all been inspired or influenced by the MEA.

The TEEB was initiated by researchers in Germany and the European Commission. Unlike the MEA, the TEEB was designed to improve decision makers' understanding of the economic significance of ecosystem services and their provided natural capital (De Groot et al., 2010). The TEEB revised the MEA classification by removing the supporting services category (which is viewed as a subset of ecological processes) and including a new category, "habitat", to highlight the importance of habitat provision. To clarify the links between ecosystem services and well-being, the TEEB connects ecosystem functions (which represent the potential or capacity for an ecosystem to deliver a service), ecosystem services, and benefits. This separation of ecosystem functions and ecosystem services was done to prevent double counting the economic value of benefits. Ecosystem services and benefits are also separated; ecosystem services are viewed as the contributions that ecosystems make to well-being as flows (e.g., a constant flowing stream), whereas ecosystem benefits are stocks created (from the combination of natural and non-natural capital) or derived by people from those services (e.g., hydroelectric power generated from a dam). Lastly, although economic benefits are the main focus of the TEEB, the system also separates benefits into ecological (i.e., valuing the integrity or health of one part of an ecosystem derived from another, such as the value of one species for the survival of another), and sociocultural (i.e., valuing biodiversity or ecosystems for their provided health, historical, ethical, religious, or spiritual significance) categories (De Groot et al., 2010).

The CICES was developed by the European Environment Agency to provide a science-based, hierarchical classification system for environmental accounting and to map the supply of ecosystem services. It was designed with the intention of supporting those interested in quantifying the value of ecosystem services, as well as those interested in assessing how human impacts alter an ecosystem's capacity to deliver services (Haines-Young and Potschin, 2012). The CICES was the first classification system to

2 CICES and NESCS (Plus) are regarded as the only true classification systems, including categories that are complete, mutually exclusive, consistent, and relevant (Finisdore et al., 2020).

3 Fisher et al. (2009) describe intermediate ecosystem services as services which stem from interactions between ecosystem structure and processes. Intermediate services ultimately lead to final services, which in combination with other forms of capital provide human welfare benefits. For example, the intermediate service of nutrient cycling leads to the final service of clean water, which can be used for drinking or irrigation. The values of intermediate services are embedded in these welfare benefits, which is why their inclusion leads to double counting.

use a hierarchical structure for classifying ecosystem services. This structure was chosen to provide flexibility in its applications across various thematic and spatial scales and includes all of the ecosystem services identified in the MEA except for the supporting services. The CICES distinguishes between final and intermediate ecosystem services, although a lack of explicit partitioning between final and intermediate services (despite excluding supporting services) may not prevent double counting (Haines-Young and Potschin, 2018; Newcomer-Johnson et al., 2020). Ecosystem services are explicitly indicated as final services that directly benefit people, while biophysical structure and function are intermediate (supporting) services. This was done to link ecosystem and economic accounts, which necessitated identifying those final services of value to people (Haines-Young and Potschin, 2012).

The National Ecosystem Services Classification System-Plus (NESCS Plus) and webtool were developed by the EPA (U.S. Environmental Protection Agency, 2015; Newcomer-Johnson et al., 2020). Like CICES, a hierarchical structure is used to classify ecosystem services; however, the NESCS Plus focuses on FEGS and takes a beneficiary perspective, linking biophysical attributes of ecosystems to specific benefits or uses for human stakeholders. The system uniquely identifies distinct categories of FEGS and the pathways through which they impact well-being, supporting quantitative analyses of benefits from ecosystem services. The NESCS Plus offers two ways to classify the human dimensions (i.e., the receiving end) of FES flows:

1. A combination of Direct Use and Direct User classes and subclasses; and
2. Beneficiary classes and subclasses.

Both approaches use hierarchical lists to support a comprehensive identification of the different ways in which humans benefit from ecosystems. Regardless of the approach selected, the user will receive results for Direct Use, Direct User, and Beneficiary classes. Using the combination of Direct Use and Direct User components provides the flexibility to separately classify: (1) how an ecological end-product or environmental attribute is used; and (2) who uses it. Following established classification structures adopted by the U.S. Census Bureau and United Nations, the first level includes broad sectors of the economy – Industry, Households, and Government. By using the North American Industrial Classification System (NAICS) system to classify who (i.e., identify the Direct User), it also offers an easy link to other information systems that use NAICS categories or codes to classify economic or other data as NAICS is the standard used by U.S. federal statistical agencies in classifying business establishments. The Beneficiary approach is simpler because it only contains one component, and thus it may be more intuitive, especially for users with less experience with NAICS. Unlike the Direct User and Direct Use/Non-Use concepts, the Beneficiary concept does not separate the questions of: (1) who benefits from nature; and (2) how they benefit. Therefore, it can be considered a combination of the two concepts.

3 NESCS Plus, common language, and decision-making

Although the NESCS Plus was designed to support systematic and comprehensive accounting of changes in FEGS, the primary motivation behind its development was to provide a robust, step-by-step resource for taking a human-centered approach to tracing the links between ecosystems and human well-being. The primary purpose of the NESCS Plus is to serve as a framework for analyzing how ecosystem changes impact human welfare. In the NESCS Plus, the EPA provides a means to standardize ecosystem services classification (e.g., Bell et al., 2017; Rhodes et al., 2017; Bolgrien et al., 2018; Littles et al., 2018; Angradi et al., 2019; Tashie and Ringold, 2019; Yee et al., 2019; Warnell et al., 2020; Jones Littles et al., 2023). This solid foundation can be used in the further use and development of ecosystem services research and in developing other ecosystem services tools that use the same "language". While the NESCS Plus provides a framework, architecture, and taxonomy it is not a decision support system on its own. Through integration with other tools like the FEGS Scoping Tool it can support decision-making. The intended audience for this resource includes individuals, communities, private and public sector firms, and non-profit organizations looking to measure, quantify, map, model, and/or value a comprehensive standard set of ecosystem services anywhere on the Earth.

The NESCS Plus lists of (1) beneficiary classes and subclasses and (2) ecological end-product categories and environmental attribute subcategories (hereafter referred to as attributes) provide the foundation for consistent and comprehensive descriptions of human benefits and the underlying ecosystem using language that is clear and easily understood by a range of audiences. No additional translation is needed when using the NESCS Plus to describe a *Recreational Hunter* who cares about *Edible Fauna* in a *Forest* to the recreational hunter and therefore to scientists, decision makers, or the general public. This clarity is essential for ensuring that these different groups have a common understanding of the ecosystem and their connections to it. The systematic and comprehensive approach supported by the NESCS Plus is also helpful for evaluating tradeoffs between the benefits, a significant advantage since a single change to an ecosystem can impact different beneficiaries in a variety of ways. Finally, the hierarchical nature of the beneficiary and attribute lists supports use of the classification system at a variety of scales. The system does not specify or limit the spatial or temporal scale and allows the system user to specify these dimensions based on their own needs and context. For example, users could choose to use the broader top-levels of the hierarchy, or they could even create their own finer nested levels by providing additional specificity to descriptions of beneficiaries or attributes, users are able to describe FEGS at more local scales while maintaining the connection to and benefits of the NESCS Plus. To return to the above example, the FEGS can be described more precisely for decision-making purposes as *Recreational Bow Hunter* who cares about *White Tail Deer* in *Francis Marion National Forest* without losing the connection to the NESCS Plus standardized language and its associated benefits.

4 The EPA's final ecosystem goods and services tools

In general, decision-making is a six-step process, regardless of whether the steps are considered explicitly (Gregory et al., 2012). Ecosystem services are a valuable inclusion at every decision step (Table 1) and researchers are working to support that (Yee et al., 2017; Fulford et al., 2023; Yee et al., 2023a). As decision makers tackle a range of decisions, with varying levels of resources, complexity, and public interest, the steps in which they include EGS will shift. To be as useful as possible to decision makers, researchers must support that flexibility with a flexible, scalable approach that can be consistently applied to increase usage, comparison, and transferability.

Researchers from the EPA are identifying and quantifying ways in which natural ecosystems contribute to healthy and sustainable communities (Harwell and Jackson, 2021). An explicit goal is to provide information and tools that help decision makers and local communities sustain such contributions, known as ecosystem services, to enhance aspects of human well-being, including economic growth and prosperity, public health, stability, and resiliency. Using the standardized framework and language of the NESCS Plus classification system allows tools and databases to interact, making it easier for decision makers to move from one to another and to combine tool use to best meet their needs for where they are in their decision process. A common language can allow tool inputs and outputs to intersect with each other and simplify communication of tool results. For decision makers, NESCS Plus addresses the question: "How do we start talking about ecosystem services?"

The EPA has four tools that can work with the NESCS Plus language: (1) the FEGS Scoping Tool; (2) the FEGS Metrics Report; (3) the EnviroAtlas; and (4) the EcoService Models Library. Each tool addresses different decision maker needs and can be used at different points in the decision-making process (Table 2). The FEGS Scoping Tool and the FEGS Metrics Report underwent development as the NESCS Plus was being finalized and each was

TABLE 1 Ecosystem services for each step in a decision process (modified from Yee et al., 2017 and Harwell et al., 2023).

Decision-making step	Why EGS consideration can bring value
Clarify decision context	Helps clarify the decision's potential impacts on stakeholders and the spatial and temporal extent of the impacts. Example activities: • Identify and prioritize stakeholders and EGS • Identify potential EGS using clearly defined terms and a comprehensive list • Find strategies for identifying relevant EGS objectives and impacts
Define objectives	Helps to identify measures related to stakeholders' relationships with the ecosystem and identify the extent to which non-EGS objectives rely upon underlying EGS. Example activities: • Identify established links between EGS and human health • Identify most relevant and meaningful FEGS metrics • Identify potential EGS using clearly defined terms and a comprehensive list • Identify and prioritize stakeholders and EGS • Find strategies for identifying relevant EGS objectives and impacts
Develop alternatives	Supports identification of creative alternatives arising from an understanding of the connections between the ecosystem and human well-being. Example activities: • Identify potential EGS using clearly defined terms and a comprehensive list
Estimate consequences	Assesses impact of the alternatives to valued EGS objectives to reduce the likelihood of unintended consequences. Example activities: • Identify established links between EGS and human health • Map people and built spaces • Find models for estimating EGS • Create conceptual model for how stressors impact EGS • Estimate stressors and impacts on EGS • Map alternative land-use scenarios and EGS, and impacts • Examine EGS risks and benefits to compare and communicate decision alternatives
Evaluate tradeoffs and select	Allows for consideration of how different options meet EGS objectives alongside other social or economic objectives. Example activities: • Find strategies for evaluating EGS • Identify and prioritize stakeholders and EGS
Implement, monitor, and review	Helps evaluate the changes on the site to measurable changes in realized benefits. Example activities: • Identify most relevant and meaningful FEGS metrics • Identify potential EGS using clearly defined terms and a comprehensive list • Find strategies for incorporating EGS into monitoring

TABLE 2 The tools discussed in this article and the generic decision-making steps at which they are potentially useful.

Decision-making step	Tools
Clarify decision context	NESCS Plus, FEGS Scoping Tool
Define objectives	NESCS Plus, FEGS Scoping Tool, FEGS Metrics Report
Estimate consequences	EcoService Models Library, EnviroAtlas
Evaluate tradeoffs and select	FEGS Scoping Tool
Implement, monitor, and review	NESCS Plus, FEGS Scoping Tool

designed to use the NESCS Plus beneficiary and attribute lists as critical structural elements. The EnviroAtlas and the EcoService Models Library were developed and released before the NESCS Plus and the common language was included subsequently. All four tools, described below, benefit from the coordinated implementation that the NESCS Plus makes possible. This creates a synergistic capacity for using multiple tools as part of a decision-making process.

4.1 The FEGS Scoping Tool

The Final Ecosystem Goods and Services (FEGS) Scoping Tool (https://www.epa.gov/eco-research/final-ecosystem-goods-and-services-fegs-scoping-tool) was developed to meet the needs of researchers and managers interested in identifying relevant EGS for a particular project, area, or decision context. It answers the question: "What ecosystem services matter?" Although this seems like a straightforward question, there are a few potential complications. First, the ecosystem under consideration will be producing, or capable of producing, a certain set of EGS. These EGS, however, may or may not be of interest. Therefore, identification of beneficiaries must be done to identify relevant FEGS. Second, ecosystems can produce a wide range of FEGS and beneficiaries are interested in a wide range of ecosystem services. The list of FEGS for any given area could be considerable and cannot all reasonably be considered or evaluated in decision-making. Extensive lists of potential items of interest are of limited utility in decision-making as they provide a wide range of options but no way of distinguishing among them (Scheibehenne et al., 2010). The FEGS Scoping Tool addresses these issues by providing users with a transparent, repeatable, and defendable approach for identifying and prioritizing the FEGS most relevant to a decision's stakeholder groups (Sharpe et al., 2020).

The importance of including stakeholder perspectives in decision-making has long been recognized (Gregory, 2000; Gregory and Wellman, 2001), but constraints may limit the extent and scope of stakeholder involvement and necessitate some degree of prioritization for inclusion. If not done explicitly, this prioritization is often done in an unconscious or *ad hoc* fashion. The FEGS Scoping Tool takes a formal approach towards stakeholder prioritization and then uses the results of that prioritization to subsequently identify and prioritize the ways in which stakeholders are connected to the environment and the specific aspects of the environment necessary for those connections (Sharpe et al., 2020). It is designed to be used at an early stage of the decision-making process. By focusing on the most relevant FEGS, rather than those most discussed or most easily measured, decision makers increase the likelihood that the consideration of FEGS will be influential in the decision-making process. By beginning the analysis with a complete consideration of all possible stakeholder groups, decision makers increase the likelihood of finding common beneficial uses among the stakeholder groups and decrease the likelihood that valued FEGS will be overlooked in the decision-making process.

The FEGS Scoping Tool uses decision criteria designed to support stakeholder prioritization (Sharpe et al., 2021). In the first stage, tool users identify stakeholder groups and prioritize them using the provided criteria. In the second stage, the NESCS Plus beneficiary lists are used to identify the ways in which each stakeholder group benefits from the potentially impacted ecosystem. The prioritization from the first stage carries through to result in a prioritized set of beneficial uses. In the third stage, the NESCS Plus attribute lists are used to identify the critical ecosystem elements for realizing each beneficial use. Again, the prioritization from the previous stage is carried through, and the result is a prioritized set of environmental attributes.

The FEGS Scoping Tool's use of the NESCS Plus language amplifies the consistency of the tool, allowing decision makers to use completed tool runs as a starting point when considering the same stakeholder groups for a new decision. This clarity, comprehensiveness, and consistency makes the FEGS Scoping Tool an effective tool for fully characterizing the FEGS relevant for a decision context and identifying the subset that should be used as decision objectives.

As an example, a multi-stakeholder driven revitalization effort at the East Mount Zion Superfund landfill site in York County, Pennsylvania focused on improving the social-ecological value of the ecosystem by creating a space for education, recreation, wildlife habitat, and enhanced biodiversity making the site an asset to the community. The team used the FEGS Scoping Tool to work through stakeholder priorities and identify desired EGS to target (Sharpe et al., 2022). In another example, the FEGS Scoping Tool was used to understand priorities of Chesapeake Bay stakeholder groups in connecting EGS – identified using NESCS Plus – and beneficiaries associated with Best Management Practices in the watershed (Rossi et al., 2022).

4.2 The FEGS Metrics Report

Interest in including EGS in decision-making has grown in recent years to more fully account for nature's contributions to human and environmental health (Posner et al., 2016). The challenge for U.S. federal agencies has been that much of the EGS research has been at small spatial extents or specific case studies, making it more difficult to consider regional and national scales at which federal policy is made. The need for a consistent metrics for EGS assessment was identified by the EPA Science Advisory Board (U.S. Environmental Protection Agency, 2009), which found – despite large, nationwide ecological monitoring programs – that analysis of EGS was problematic due to a lack of specific metrics that can represent changes in ecosystem services (e.g., Chestnut and Mills, 2005), and a lack of specific stakeholders who may benefit from these services (Ringold et al., 2013; U.S. Environmental Protection Agency, 2020). In this context, the EPA co-developed a standardized process to identify metrics that allow decision makers to answer the question: "How to measure what matters?"

This process, arising from a collaboration between social and natural scientists, was formalized in 2020 with the publication of the EPA report *Metrics for national and regional assessment of aquatic, marine, and terrestrial final ecosystem goods and services* (U.S. Environmental Protection Agency, 2020). Because these metrics have joint validity with both natural and social scientists, they can be used for interdisciplinary analysis across disciplines. This report helped to operationalize these ideas by providing specific metrics that can be used by both natural and social scientists for analysis. These metrics serve as linking indicators between these different ways of knowing and analyzing ecosystem services (Boyd et al., 2016). This joint validity exists because FEGS serve as the end-products of ecological systems and the inputs into social systems. Further, the report focuses on metrics that measure specific, tangible biophysical features or qualities that are relevant for management and that are provided in units that require little to no technical explanation. Beyond linking different scientific disciplines, these metrics also facilitate communication to lay audiences involved, invested, or interested in changes to the ecosystem being measured.

The metric report lays out a standardized, five-step process that can be used to identify metrics (U.S. Environmental Protection Agency, 2020):

1. Recognize ecosystem boundaries from the perspective of natural scientists.
2. Specify beneficiaries who use, interact with, or enjoy the ecosystem services created by the ecosystem.
3. Identify the biophysical components of nature that link the ecosystem and the beneficiary's interests.
4. Describe the metrics for each beneficiary/attribute combination (e.g., each FEGS).
5. Consider the data availability of the potential metrics.

The report itself also includes suggested metrics for seven ecosystem types (coral reefs; estuaries; lakes; rivers and streams; wetlands; agricultural lands; forests) and more than 40 different beneficiaries as a starting point and example of the process.

As with the FEGS Scoping Tool, the FEGS Metrics Report was built upon using the NESCS framework to help users specify the biophysical measures that were most relevant for a specific beneficiary/attribute combination. The Report benefits from the NESCS Plus framework being sufficiently comprehensive for encompassing all beneficiary/attribute combinations for which metrics may be needed as well as from its scalability, allowing users to craft metrics relevant to assessments ranging from the national to the local. Communicability, comprehensiveness, and scalability make the FEGS Metrics Report an effective tool for identifying decision objective measures that can be used when estimating consequences.

Although the report was not publicly available at the time of the work conducted in Chesapeake Bay, researchers used the same foundational framework as the report (Ringold et al., 2013) when identifying the metrics most relevant to priority FEGS. Those metrics assist managers in encourage adoption of Best Management Practices by connecting them to the beneficial uses valued by the community (Rossi et al., 2022).

4.3 EnviroAtlas

The EnviroAtlas (https://www.epa.gov/enviroatlas) allows users to visually interpret ecosystem services and understand how they can be included in decision-making efforts, answering the user question: "How to map what matters?" The EnviroAtlas was developed collaboratively between the EPA, the U.S. Geological Survey, the U.S. Department of Agriculture, and other federal and non-profit organizations, universities, and communities including state, county, and city-level stakeholders. The EnviroAtlas is an online mapping resource containing more than 500 geospatial data layers for the U.S., including environmental and socioeconomic related data and tools that can be used to examine a location and characterize the ecological and socio-economic status (Pickard et al., 2015). These data can be used in an EGS framework. Using an interactive, online map approach, the EnviroAtlas contains EGS data organized into several categories characterizing the production, demand, and the EGS attributes that may affect an ecosystem's ability to produce EGS. The EnviroAtlas has seven overarching EGS benefit categories: food, fuel, and materials; clean air; recreation, culture, and aesthetics; natural hazard mitigation; climate stabilization; clean and plentiful water; and biodiversity and conservation.

The EnviroAtlas was designed for multiple audiences, (e.g., individual, government, or organization with an interest in the environment) and for use without special expertise. There are many potential applications of EnviroAtlas, including green infrastructure, brownfields, community planning, stormwater management, mitigation banking, and climate change resiliency, such as urban heat island abatement planning. The EnviroAtlas contains data at two primary scales. Many data layers are available at the national scale, with approximately 97,000 sub-watershed hydrologic unit codes (HUC 12) for the conterminous U.S. (ranging from 39 to 160 km^2 each). Most of the community data layers are summarized at the U.S. census block scale. Additionally, 1-meter resolution land cover data exists for over 1,400 U.S. municipalities. The EnviroAtlas includes two climate change tools in an interactive mapping application. Additionally, the EnviroAtlas includes ecosystem markets data layers for market initiatives and enabling conditions at a range of scales. Although EviroAtlas was released prior to the NESCS Plus, the EnviroAtlas now includes a searchable matrix which crosswalks EnviroAtlas metrics with FEGS; again, providing a connection to the language of the NESCS Plus (Tashie and Ringold, 2019).

Bolgrien et al. (2018) used the EnviroAtlas to guide selection of EGS indicators, which were used as endpoints in a framework used to help stakeholders evaluate the community's land use and infrastructure recommendations.

4.4 EcoService Models Library

In an ideal world, there would be ample time and money to measure all the EGS and FEGS that matter in every scenario. In the real world, time and money are often limited. After using the FEGS Scoping Tool and the FEGS Metric report to identify the FEGS and metrics that matter the most in a given scenario, it may not be feasible to measure them all so modeling may be a useful alternative. The EcoService Models Library (Bruins et al., 2017; DeWitt et al., 2020; Newcomer-Johnson, in press; https://www.epa.gov/eco-research/ecoservice-models-library) was developed to address the question of "How to model what matters?" by helping users find models to estimate the production of ecosystem goods and services.

The EcoService Models Library is a searchable database containing detailed descriptions of over 280 ecological models, their variables, and the source documents that describe them for use in estimating the production of ecosystem goods and services. Relationships potentially described as ecological models can vary widely in complexity, presentation, and subject matter. Some like InVEST and i-Tree are elaborate simulation tools with software, manuals, and websites (e.g., Nowak et al., 2013; Smith et al., 2017), while others are simple equations not found beyond the pages of a journal article (e.g., Bellinger et al., 2014), an ecological model can draw from a single discipline (e.g., a predator–prey interaction) or many (e.g., including physical–chemical–biological, and potentially social–political–economic elements). The EcoService Models Library was developed to help planners, analysts, risk assessors, economists, and other scientists to understand and select useful ecological models. A secondary purpose is to help researchers interested in improving ecological modeling methods.

Ecological models can be useful for linking ecosystems, stressors, and management actions to the production of EGS and FEGS. The ideal model for a particular issue should address the desired modeling objectives, should apply within the appropriate environmental context, would require the right degree of effort and expertise, and should characterize the level of uncertainty (Bruins et al., 2017). The EcoService Models Library's 20 pre-defined filters are more powerful for most uses because they examine the EcoService Models Library classification-based descriptors; the pre-defined filters are source/collection, environmental sub-class, ecosystem services, hazardous waste site ERA, location, variable classification, time dependence, time continuity, spatial extent area, spatial distribution, computational approach, determinism, statistical estimation, calibration performed, goodness of fit reported, uncertainty analysis performed, ecological scale, and organismal scale. The filters can be used in combination to increase search specificity.

Most entries in the EcoService Models Library describe specific applications of models. Since model formulations often change from one application to the next, focusing on a specific application minimizes the problem posed by model versioning. Applications also include valuable information on context and often on uncertainty as well. Each model entry includes over 50 individual descriptors covering the model identity and description, modeling approach, location, environment, ecology, EGS potentially modeled by classification systems, and variable names. The environmental components (and language) of the NESCS Plus and the CICES are included. A variable relationship diagram, showing logical relationships between variables, is provided for each ecological model (Bolgrien et al., 2018). In addition to its main purpose of finding models, users can also find information about variable values used in model applications and examine the potential for linking models by sorting variables into Variable Classification Hierarchy top level categories. Each model variable is described by 40 additional descriptors. These variable descriptors are divided into variable general information, typology, spatial characteristics, temporal characteristics, values, variability and sensitivity, and operational validation.

In addition to links to the NESCS Plus classification system, the EcoService Models Library also has links to the EnviroAtlas (Bolgrien et al., 2018). For example, the EnviroAtlas is included as one of the collections that users can search for finding models (Figure 1). Additionally, an EnviroAtlas URL is included when data from the EnviroAtlas may be helpful for finding data to run the models found in the EcoService Models Library. The EcoService Models Library also includes links to EnviroAtlas fact sheets that provide information on how the data were created, limitations of the data, how to access the data, where to get more information, and references for selected publications. The EcoService Models Library matches ecological model variables to potentially useful EnviroAtlas data layers based on how the variables were classified in the Variable Classification Hierarchy, a classification system that bins variables into informative categories to enable searching and investigation of models based on their variable characteristics.

Returning to the East Mount Zion example, the revitalization team also used the EcoService Models Library to ultimately identify five ecological models (e.g., carbon storage and sequestration, pollinator populations, rare species, and bird populations)

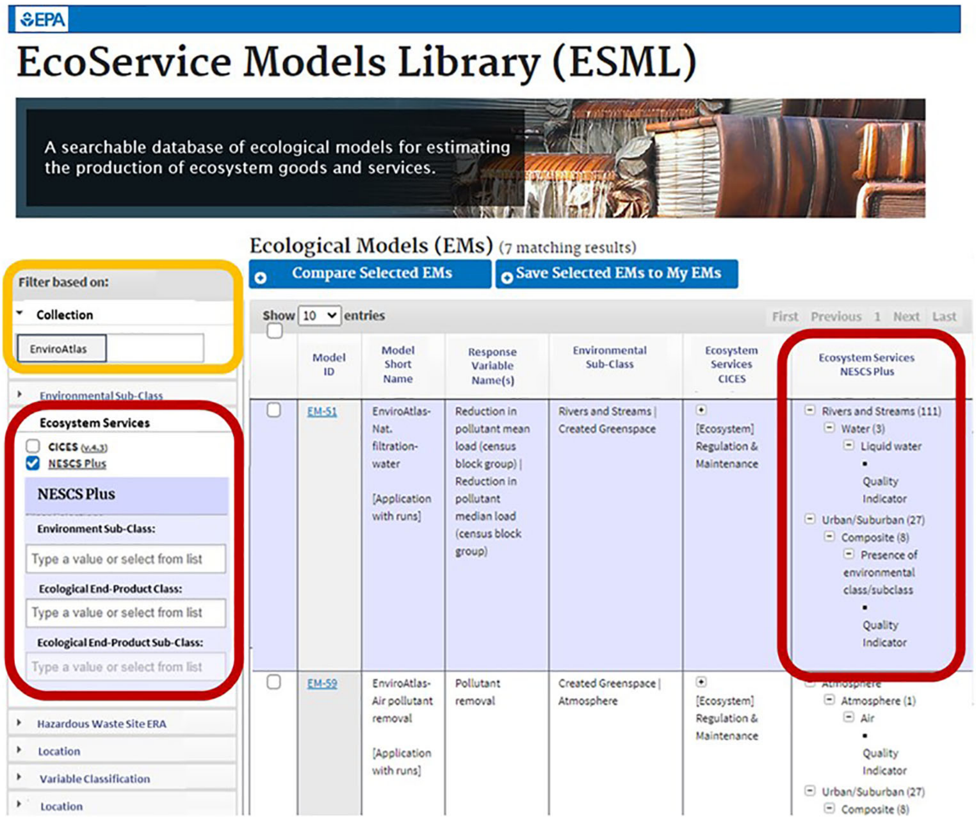

FIGURE 1
The EcoService Models Library (ESML) offers users the ability to find models using filters such as ecosystem services, using the NESCS Plus classes and subclasses (red boxes), as well as collections such as EnviroAtlas (yellow box).

relevant to their targeted EGS to apply to examine scenarios. As a result, the team was able to examine a broader suite of EGS they might not have otherwise identified as target endpoints. The EcoService Models Library was also used in the Chesapeake Bay example to help identify potentially relevant metrics.

5 More powerful than the sum of their parts

We posit that using multiple tools with the common anchoring point of the NESCS Plus framework creates a synergistic effect, much like the synergistic effects realized by using multiple teaching tools in a hybrid learning environment (Cai and Wang, 2022) or the synergistic effects of the legendary *Voltron*: *Defender of the Universe*, a robot with greater strength and skill than the five individual robot lions that make it up (Keefe, 1984–1985). The East Mount Zion example above used two of the four tools. By coupling the application of the FEGS Scoping Tool with the EcoService Models Library, the team realized synergistic outcomes not realized elsewise. Using the FEGS Scoping Tool to capture the community's relationship to the site supported straightforward and evidence-based selection of the models chosen from the Library to assess future site scenarios and consistent use of the NESCS Plus beneficiary and attribute categories reduced the need for explanations as the team moved from identifying EGS to prioritizing them and modeling them. For East Mount Zion, working with multiple tools was more powerful than the sum of their parts and it led to more informed alternatives for their decision-making process.

These tools are applicable to different parts of the decision-making process and are useful, alone or together, for managers attempting to make decisions or take actions with an environmental component. However, incorporating one new tool into management processes can be time-consuming and unappealing to managers who are often both resource and time-limited, let alone incorporating multiple new tools. How priorities are chosen depends on the user and the decision context. As a result, an ecosystem services assessment tool selection portal was developed to walk the user through which tools are relevant for different parts of a generic, structured decision-making process (Harwell et al., 2023).

Given the recency of some of the tools' release, we do not yet have a published example of all four tools being used together in the field. We do, however, have multiple examples that demonstrate the value of the tools when used in combination. In East Mount Zion, the consistent language provided clear connections between stakeholder values and the ecosystem service models selected to evaluate site scenarios. In Chesapeake Bay, tool compatibility allowed researchers to use one tool (the FEGS Scoping Tool) to gather and organize information on community priorities and two other tools (the FEGS Metrics Report, the EcoService Models Library) to select metrics responsive to those priorities and associated with the management organization's Best Management Practices. Although the FEGS Scoping Tool was not yet publicly available at the time of the Milwaukee case study, researchers flagged its utility for use in combination with the EnviroAtlas and how it could be used within their framework (Bolgrien et al., 2018). Finally, the FEGS Scoping Tool, the EcoService Models Library, and EnviroAtlas were selected for coordinated demonstrations at a workshop aimed at exploring the incorporation of EGS tools into the ecological risk assessment process for contaminated sites (Kim et al., 2023).

5.1 Synergistic example

The above examples support our contention that the consistent EGS framework of the NESCS Plus would allow for the easy integration of all four tools into a single decision context. To that end, we lay out a hypothetical example using a common scenario demonstrating how that might be done. Pensacola Beach, in the Florida Panhandle, is known for its ultra-white sand beaches and is located just south of Pensacola, the second largest city in the Panhandle. A popular tourist destination and local resource, the land is owned by the government and leased to private and public entities. Currently, 60% of the land is held for public use with the rest leased for residential or commercial uses. For the purposes of this example, we consider a scenario in which county commissioners are evaluating the proposed construction of a new beachfront hotel.

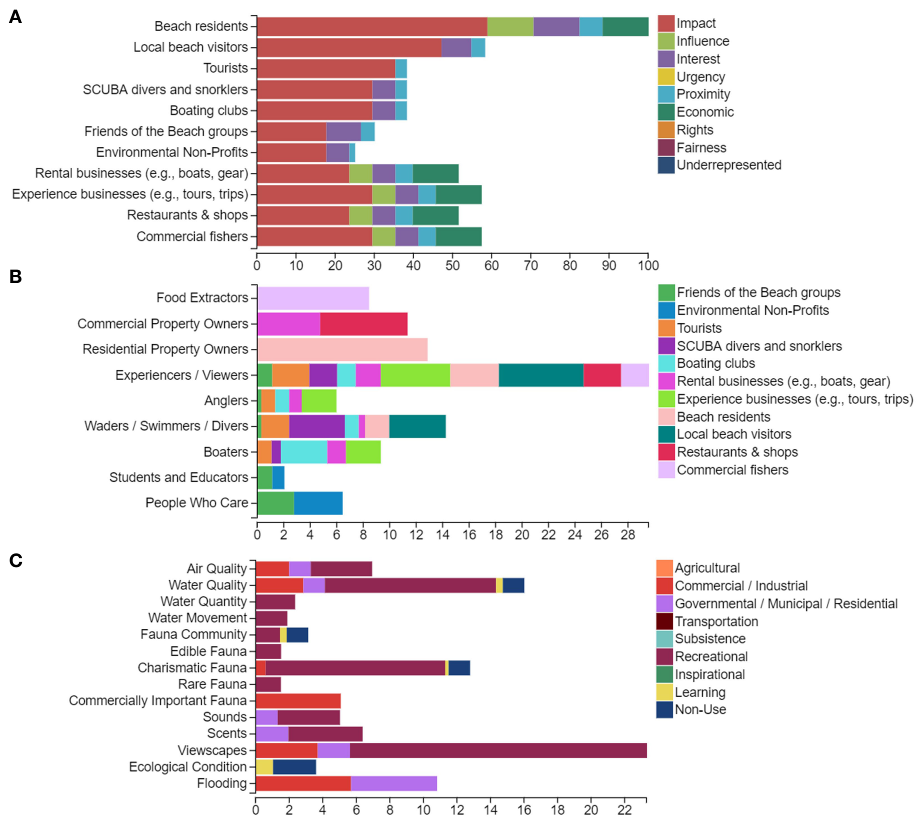

FIGURE 2
An example set of the FEGS Scoping Tool outputs. Panel **(A)** is a stakeholder prioritization (stage 1). It is the result of users weighting a set of decision criteria to reflect their values being used in this decision and scoring stakeholder groups on the extent to which they meet the criteria using tool-provided rubrics. These results arise from the hypothetical example in which commissioners are using the tool to prioritize stakeholder groups and the EGS they value when assessing the beachfront hotel development proposal. Here beach residents are a high-priority group because of the potential impact this decision would have on them. Panel **(B)** is a beneficiary group prioritization (stage 2) resulting from commissioners identifying the beneficiary groups making up each stakeholder group. Here we see beach residents benefiting as property owners, but also as experiencers/viewers and swimmers and divers. Panel **(C)** is an environmental attribute prioritization (stage 3) resulting from commissioners identifying the attributes needed for each beneficial use. For example, to enjoy their benefit, swimmers and divers need attractive viewscapes and charismatic fauna as well as water safe for immersion. The Scoping Tool outputs help commissioners identify the stakeholder groups (e.g., beach residents) whose perspectives should be included in decision-making and the ecosystem services that matter to them (e.g., the viewscapes from homes on the beach and the risk of flooding to those homes).

Commissioners might begin by selecting the criteria to use when evaluating the development proposal. There are several socio-economic criteria that can be easily identified (e.g., jobs created, tax revenue, traffic, infrastructure needs). The FEGS Scoping Tool, anchored to the NESCS Plus, can help them identify EGS criteria that should be considered as well (Figure 2). In this example, commissioners review the tool's list of stakeholder prioritization criteria and set "Magnitude and Probability of Impact" as the most important criterion for distinguishing among stakeholder groups. The FEGS Scoping Tool results indicate that those currently living or working on or near the beach (residents, rental and activity businesses, shops and restaurants, and commercial fishers) are the highest priority stakeholder groups (Figure 2A). Stakeholders benefit from the area in primarily recreational ways, and every stakeholder group benefits to some degree by being able to engage in experiencing/viewing activities. Wading, swimming, diving, and property ownership are also beneficial roles of high importance (Figure 2B). The results identify priority ecosystem services as viewscapes, water quality, and charismatic fauna for recreational uses and flooding related to commercial and residential uses (Figure 2C). This points the commissioners to including criteria related to these services alongside the socio-economic criteria when evaluating the proposal.

Once priority EGS have been identified, the commissioners need appropriate metrics to assess them. For some of the EGS, the FEGS Metrics Report can suggest metrics along with information about available datasets. Those metrics are organized by ecosystem type and identified using the same beneficiary and attributes lists as the FEGS Scoping Tool. For example, Table 3 contains metrics from report for viewscapes, water quality, and charismatic fauna for a range of recreational uses. For those criteria which do not have a corresponding metric in the report or for those where the suggested metric is inappropriate, the report contains guidance for developing more using the same format. In those cases, the results from the FEGS Scoping Tool can be used to complete the first three steps in the metrics identification process.

After the commissioners have identified and decided how to measure changes to priority EGS, they may be interested in assessing how those services may be impacted under different development scenarios. To do this, they can turn to the EcoService Models Library. Using the EcoService Models Library filtering system, they will easily be able to target models relevant to their priority services and metrics. For example, using the Ecosystem Service filter, they can find 12 models relevant to "Scapes: views, sounds and scents of land, sea, sky, or a combination." By reviewing the models' response variables, the commissioners can easily find the set of models most helpful in evaluating development scenarios (Table 4).

In addition to potential changes related to the production of EGS, commissioners are likely interested in the spatial distribution of priority services. Use of the FEGS Scoping Tool allowed the commissioners to identify charismatic fauna for recreational uses as a priority service and the FEGS Metrics Report suggested to measures of species diversity and presence. Now, the EnviroAtlas allows them to visualize data related to species richness and rarity, aspects of charismatic fauna that matter to a range of recreational beneficiaries (Figures 3A, B). The FEGS Scoping Tool also identified flooding for residential and commercial uses as a priority EGS and the commissioners can use the EnviroAtlas to find maps of flooding and sea-level rise (Figure 3C). The EnviroAtlas can also allow commissioners to visualize aspects of flooding related to the costs and viability of property ownership and to compare the suitability of different sites for the proposed development activity if 1-m resolution data are available.

Together, these tools allow the commissioners to identify the EGS of greatest concern to their stakeholder groups, determine how best to measure changes to those services in terms that are easily understood by a wide variety of audiences, and discover useful resources for exploring current and future levels of service production and spatial distribution. The tool ensemble allows for comprehensive consideration of EGS such that EGS criteria can be included in decision-making alongside the socio-economic criteria many decision makers are more familiar using. With this set of tools, the commissioners can feel justified in their decision of which EGS to include and how they are being evaluated.

6 Discussion

In our hypothetical Florida Panhandle example, we see that together, all four of these tools can work synergistically to allow the commissioners to more comprehensively consider how the EGS and uses valued by their constituents could be impacted by the proposed development than through the use of just one tool and allow for smoother integration than tools with different descriptions of EGS would permit. The FEGS Scoping Tool helps them focus on a finite list of priority ecosystem services and points them towards selection of metrics using the FEGS Metric Report process. The prioritized attributes can be used as search terms within the EcoService Models Library and the EnviroAtlas to facilitate identification of spatial data and models for estimating potential future changes. At every step throughout the process, the commissioners have a clear and communicable rationale as to which services they are focusing on and how those priority services pointed to the data used to make the decision. This consistency means that once the original EGS selection is complete, questions of which models and data to use are also answered. By anchoring these tools with the NESCS Plus language, the commissioners also have a consistent set of clear terminology they can use as part of their strategic communication efforts.

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TABLE 3 Example FEGS metrics for viewscapes, water quality, and charismatic fauna for a range of recreational uses (adapted from U.S. Environmental Protection Agency, 2020).

Beneficiary			Attribute		Biophysical metrics		Datasets				
Beneficiary	Specific beneficiary	What matters directly to this beneficiary?	Subcategory	Specific attribute	Ideal	Currently available	Data source	Scale (national, regional, local) Extent	Temporal dimensions	Currently described over large areas via remote sensing? (yes/no)	Existing capacity to model over large extents? (yes/no)
Anglers	Catch & Release	Is this area aesthetically enjoyable?	Site Appeal	Scents & Viewscapes	Color of water, algae, clarity & smell, lack of sound	Local reports	Online Posting	Local	Seasonal	No	No
Boaters	Kayakers, SUPs, and Boaters	Is this reef aesthetically enjoyable?	Site Appeal	Scents & Viewscapes	Water clarity	Field crew opinion	Word of mouth, local bait & tackle shops, local radio & TV fish reports	NA	Daily	No	No
Waders, Swimmers, and Divers	Scuba Divers and Snorkelers	Is there interesting enough viewscape to entertain divers?	Site Appeal	Viewscapes	Colors, shapes, diversity, movement	Local reports	Online posting	NA	–	No	No
Anglers	Catch & Release	Is WQ sufficient to be safe for angling?	Water Quality	Chemicals & Contaminants	Personal contact with contaminants from water	Contaminant concentrations in water	NARS; EMAP	National, Regional	Single sample during baseflow	No	No
Boaters	Kayakers, SUPs, and Boaters	Is the water in the wetland safe for recreational boating?	Water Quality	Contaminant from water exposure (chemical & biological)	Individual wetland contamination metrics	Levels of harmful bacteria; levels of chemical contamination	2011 NWCA; EPA sources	National	–	No	No
Waders, Swimmers, and Divers	Scuba Divers and Snorkelers	Is there sufficient visibility to be pleasurable to divers?	Water Quality	Water Clarity	Secchi disk	Diver recorded visibility	Online posting: diver recorded visibility; NOAA: satellite	Local	Daily	No	No

(Continued)

TABLE 3 Continued

Beneficiary			Attribute		Biophysical metrics		Datasets				
Beneficiary	Specific beneficiary	What matters directly to this beneficiary?	Subcategory	Specific attribute	Ideal	Currently available	Data source	Scale (national, regional, local) Extent	Temporal dimensions	Currently described over large areas via remote sensing? (yes/no)	Existing capacity to model over large extents? (yes/no)
Boaters	Kayakers, SUPs, and Boaters	Will I see what im expecting or any interesting animals?	Charismatic Fauna	Taxa & Presence	Species, size, abundance, diversity	Species, size, abundance, diversity	U.S. FWLS, NOAA, State fisheries departments (FWC)	Local Observations Aggregated to States Regions and the Nation	Seasonal	No	Yes
Waders, Swimmers, and Divers	Scuba Divers and Snorkelers	Do these species attract the beneficiary?	Charismatic Fauna	Taxa & Presence	Large marine organisms	Presence/ absence	EPA, NOAA, State	Regional	Seasonal	Depends–species	Yes
Anglers	Catch & Release	Will I catch something interesting?	Charismatic Fauna	Taxa & Presence	Species, size, abundance, diversity	Presence/ absence	State, Federal	Local Observations Aggregated to States Regions and the Nation	Seasonal	No	Yes

In the first part of our hypothetical example, the FEGS Scoping Tool was used to identify the priority ecosystem services, including viewscapes, water quality, and charismatic fauna for recreational uses. Once identified, commissioners can use the FEGS Metrics Report to find example metrics or to find the process for developing additional metrics. This table contains a subset of the metrics found in the report that the commissioners could use when assessing the development's potential impact to priority recreational ecosystem services. NA, Not applicable.

TABLE 4 A subset of the results from an EcoService Models Library search for models related to viewscapes, soundscapes, and scentscapes.

EM ID	EM-193	EM-713	EM-419	EM-683	EM-686
Model Name	Cultural ecosystem services, Bilbao, Spain	ESII (Ecosystem Services Identification and Inventory) Tool, MI, USA	ARIES (Artificial Intelligence for Ecosystem Services) Scenic viewsheds for homeowners, WA, USA	Value of recreational use of an estuary, Cape Cod, MA, USA	Estuary recreational use, Cape Cod, MA, USA
Response Variables	Aesthetic quality of the landscape Recreation provision index	Aesthetics: noise (noise attenuation) Aesthetics: visual (visual screening)	Enjoyed views (actual source of scenic viewsheds for homeowners) Potential views (theoretical source of scenic viewsheds for homeowners) Ratio of actual to theoretical source of scenic viewsheds for homeowners	Estimated daily beach visitation Estimated daily visitation using landings and way to water/site Estimated daily visitors using boats Total estimated daily visitation	Percent daily boating use Percent daily kayaking/stand-up paddleboarding or rowing use Percent daily spending time by the shore use Percent daily walking use

Clicking the EM-ID number will take you to that model description in the online library. In the first and second parts of our hypothetical example, the FEGS Scoping Tool was used to identify the priority ecosystem services, including viewscapes for recreational uses, and the FEGS Metrics Report was used to identify potential metrics for measuring those services. In a third step, commissioners can use the EcoService Models Library to find models relevant to those services. This table contains a subset of the models found in the Library that the commissioners could use to predict the development's potential impact to viewscapes.

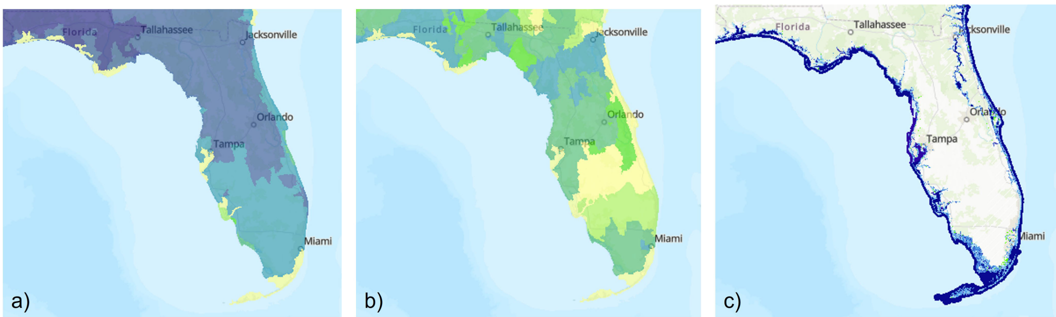

FIGURE 3
The EnviroAtlas data layers related to species richness **(A)**, rarity **(B)**, and sea level rise **(C)**. In the first and second parts of our hypothetical example, the FEGS Scoping Tool was used to identify the priority ecosystem services, including charismatic fauna for recreational uses and flooding for residential and commercial uses, and the FEGS Metrics Report was used to identify potential metrics for measuring recreational services, including species diversity and presence. Commissioners can search the EnviroAtlas to find data layers relevant to those priority services and metrics. This figure shows a subset of the data layers relevant to these services and metrics.

addition to on-going work to utilize three or more of these tools under different decision context examples, we are exploring the next suite of EGS and FEGS tools using the NESCS Plus framework and language to set the stage for additional tools to ultimately connect to these existing tools. For example, the document analysis R code used in Yee et al. (2019), Yee et al. (2023a) and Jackson et al. (in press) focuses on development and application of an automatic document reader looking for FEGS word triplets (i.e., groupings of words capturing environment type, beneficiary/user, and environmental attribute). This too is anchored in the language of the NESCS Plus. As another example, from a social science perspective, researchers are compiling a large database of EGS case studies that includes information on a large suite of parameters – including language from the NESCS Plus – to allow for further analysis of governance (Yee et al., 2023b). The NESCS Plus has also recently been used to facilitate natural capital accounting for developing supply and use tables, to give a more complete picture of a local area's environmental-economic trends (Warnell et al., 2020). Finally, as mentioned above, researchers have also recently developed an EGS assessment tool selection portal (Harwell et al., 2023) allowing the user to better understand what tool might be relevant for a given type of decision-making need (sensu Table 2). All of these efforts are focused on the core principles of having anchoring language to the NESCS Plus and are aimed at creating opportunities for increasing the synergistic powers of multiple tools being used at the same time. As different case study applications proceed, researchers will continue to refine our understanding of different ways these tools can be applied and develop ideas for enhancing tools or create new ones. The larger scientific community is invited to help us along this journey to facilitate further use of FEGS into decision-making. These tools are publicly available and can be used off-the-shelf to assist researchers and practitioners in better integrating ecosystem services into decision-making processes, and thus improving human and community well-being.

Author contributions

LS: Conceptualization, Writing – original draft, Writing – review & editing. MH: Writing – original draft, Writing – review & editing. CP: Conceptualization, Writing – original draft, Writing – review & editing. GG: Writing – original draft. TN-J: Conceptualization, Writing – original draft, Writing – review & editing.

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Enhancing multiple benefits of brownfield cleanups by applying ecosystem services concepts

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Brownfields are increasingly called upon to be transformed from potentially contaminated, often vacant properties into community assets that provide multiple benefits. Further, brownfields revitalization can provide critical opportunities and, particularly, nature-based solutions can enhance multiple ecological, human health, and economic benefits. Through a series of non-exhaustive surveys of existing examples of environmental benefits of cleanups, case study examples of brownfield cleanups achieving environmental benefits, and potential ecosystem services tools relevant to steps of a brownfields cleanup effort, we explore practical ideas for enhancing environmental benefits of brownfields cleanups by applying ecosystem services concepts. Examples of nature-based solutions, where appropriate, include the use of rain gardens, permeable pavements, green spaces, and the use of green technologies. Further, this article provides an overview of recent policy initiatives focused on nature-based solutions and enhancing ecosystem services in brownfields cleanup, revitalization, and reuse. Our goals are to increase the knowledge base on these opportunities and discuss how these concepts can be achieved through sharing success stories, making outreach materials accessible, and holding workshops to help successfully operationalize these concepts in a community's visioning for upcoming revitalization projects.

KEYWORDS
brownfields, nature-based solutions, ecosystem services, environmental policy, environmental benefits

1 Introduction

Finding the balance in decision-making between rapidly growing societal needs and the goal of preserving, restoring, or enhancing the benefits that nature provides to people to help with resilience and sustainability is an ever-growing challenge. Ecosystem services are "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" (Daily, 1997). Ecosystem services as a concept provides an opportunity to identify, quantify, and evaluate ecosystem condition, status, and change associated with a decision, and describe the provisioning of environmental benefits to people to inform alternative selection, trade-off analyses, and cost-benefit analyses to support environmental decision making (Fisher et al., 2009). In recent years, ecosystem services have been at the forefront of efforts focusing on providing environmental benefits for human needs. For example, cleaning up contaminated lands, whether for commercial, residential, recreational, or greenspace use can result in jobs created for local residents, increases in property value, and provision of other services that contribute to improving a community (O'Sullivan et al., 2017). One type of land cleanups are brownfield sites, which are typically abandoned, idle industrial properties that have potential for redevelopment once environmental contaminants are removed (BenDor et al., 2011). The benefits of revitalizing brownfield areas may include economic, social, and environmental benefits (Söderqvist et al., 2015). Strom (2018) provides an overview of brownfield cleanups in urban environments, focusing on the importance of bringing together a suite of stakeholders interested in urban development and environmental concerns.

The aim of brownfield revitalization is to ultimately support sustainable and efficient redevelopment and employment opportunities, and the process of remediating contaminated sites creates opportunities for pursuing environmental restoration and community revitalization of the land (Williams and Hoffman, 2020). Each component allows important opportunities to develop and apply approaches to enhance social, economic, and environmental benefits. Regardless of where a given brownfield site is in the overall cleanup process (pre-development, development, management) or ultimate endpoint (remediation, restoration, or revitalization), understanding both economic and environmental benefits of cleanups can help with cost-benefit analyses, a key element in identifying productive and attractive revitalization options for stakeholders (Haninger et al., 2017). While this article introduces ecosystem services concepts, it is important to recognize different terminology might be used by different stakeholders when describing benefits that nature and ecosystems provide. Here, we use the term "environmental benefits" as this term is better understood by a wide range of stakeholders.

One primary area of promoting environmental benefits resulting from brownfield cleanups is the application of green design or nature-based elements, ranging from including green spaces to using green infrastructure as part of the remediation work. In general, the incorporation of green spaces and infrastructure elements can take form in a variety of ways from planning open spaces (e.g., landscape design of natural parks) to green roofs, nature trails, and permeable parking lots (Lewis et al., 2018). A green space design element creates an undeveloped piece of land that's accessible to the community for use as parks, community gardens, and public plazas. These types of open spaces provide recreational areas to enhance the environmental quality and aesthetics of a neighborhood. While green spaces are aesthetically pleasing, they are also an important resource for providing people access to nature while living in cities. For example, a former 200-acre industrial brownfield site in Milwaukee, WI, known as "Milwaukee Road" was redeveloped into an energy efficient, green facility, including providing access to nature. This redevelopment included 70 acres of greenspace for reestablishing pre-industrial ecosystem conditions while also protecting the location from further environmental damage (Lewis, 2008). Within these 70 acres, the community has access to three separate parks, each with different amenities. Chimney Park has two chimney stacks to pay homage to the history of the Milwaukee Road as well as parks space and recreational athletic courts. River Lawn Park provides canoeing and kayaking launches as well as a network of walking and biking trails. The adjacent Airlines Yards Park is 23 acres of natural habitat, native vegetation, and access to 2,600 feet of riverbank (Lewis, 2008). Together these parks provide the community with a variety of opportunities to learn about the city as well as enjoy the environment around them. While green infrastructure approaches encompass a large variety of practices and definitions, the main goal of incorporating green infrastructure elements into this project was to provide economical and effective approaches to support water management efforts for restoring and protecting the natural water cycle. Examples include restoring wetlands, use of bioswales, and planting trees.

The U.S. Environmental Protection Agency (US EPA) estimates that there are over 1 million brownfield sites in the United States (US EPA, 2023b). Accomplishing a successful "Brown-to-Green" project can not only be aesthetically pleasing but also be leading examples in sustainable redevelopment. According to a U.S. Department of Energy survey, the U.S. has over 5.9 million commercial buildings in 2018 (US DOE, 2020), providing opportunities to consider redeveloping spaces into energy efficient "green" building designs, and consideration of other sustainable efforts. Brownfield cleanup initiatives and designs are community specific, often tied to the footprint and history of a given property. As a result, having the community involved in visioning such projects allows them to identify what they want and what would be most beneficial to the community.

Research to address brownfield issues includes development of remediation technologies, risk and environmental assessment, and stakeholder (community and public) engagement and communication (Brebbia, 2006). Recent work has focused on highlighting environmental benefits at brownfield sites, including connections to human health, the community, and surrounding wildlife (Mastervich and Harwell, 2022). The objectives of this article are to introduce concepts of environmental benefits to the cleanup of brownfield sites, explore examples of environmental benefits achieved from brownfield cleanups, and discuss how to bring these types of benefits into brownfield planning efforts.

2 Anatomy of brownfield cleanups

2.1 Overall process

Since 1995, the US EPA's Brownfield and Land Revitalization Program has focused on a results-oriented program to help communities manage contaminated properties (US EPA, 2023b). The anatomy of a brownfield cleanup is dependent on the site and its contamination. In the conceptual framework of the decision-making process, five steps shown in Figure 1 demonstrate the cleanup process beginning with Site Assessment and ending with elements of Redevelopment. A cleanup begins with an environmental Site Assessment designed to help the community better understand if the current environmental conditions at the property are considered harmful. During this phase, surface soil, water, and sediment samples may be taken to investigate the specific hazards that are present to achieve a better understanding of the type of funding that will be needed for cleanups. A site is not only inspected during a Site Assessment, but investigations are also conducted to help determine who is potentially liable for the contamination on the site. During the Site Investigation phase, the US EPA's Brownfield program provides direct funding for brownfield assessment, revolving loans, technical assistance, research, training, and cleanup (US EPA, 2023b). Resources from the US EPA Brownfield program, federal partners, and state agencies are identified for the brownfield grant activities, including assessment grants, revolving loan fund grants, cleanup grants, multipurpose grants, job training grants, and the State and Tribal Response Grant program. The Cleanup Options design process uses a risk-based cleanup approach to help determine the level of cleanup needed at a brownfield property. During the Cleanup Design and Implementation phase, the amount of engineering and institutional controls identified for a cleanup depends on the anticipated future plans of reuse for the site. After cleanup, the site is ready for the Redevelopment Phase. Ideally, an economic perspective is also considered when determining the cleanup process to create the most successful redevelopment for the community. Further, initial visioning of future land use can be brought into early aspects of the cleanup process. This can be important for the consideration of sustainable or nature-based remediation solutions into planning and design (e.g., relying on intrinsic capabilities of some plants, bacteria, and fungi to detoxify soils and groundwater) and inform a larger discussion about future green elements and green uses at a given site.

2.2 Recent U.S. policy tools encourage enhancing ecosystem services in brownfield revitalization

United States policy initiatives increasingly encourage land revitalization that enhances ecosystem services and applies nature-based solutions. These policy initiatives and related tools provide opportunities to restore and enhance multiple ecosystem services in land revitalization, such as projects in brownfields. The message of the importance of enlisting nature-based solutions to fight climate change is evident in the 2022 White House Office of Science and Technology policy "Opportunities for Accelerating Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, and Prosperity," which focuses on enhancing or providing ecological habitats/ecologically-based solutions, including relevant to community development and economic revitalization, that provide multiple ecosystem services while addressing bigger, more comprehensive issues like climate change. This roadmap highlights nature-based solutions as "actions to protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges, simultaneously providing benefits for people and the environment" (White House Council on Environmental Quality, White House Office of Science and Technology Policy, White House Domestic Climate Policy Office, 2022). In 2021 the White House Executive Order, "Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis" (EO 13990), recognizes the value of ecosystem services in accounting for the benefits of reducing climate pollution (White House, 2021). This is relevant to reducing and mitigating toxins in our local ecosystems, which is a core goal of brownfields planning, cleanup, and reuse. Subsequently, in 2022, the Executive Order "Strengthening the Nation's Forests, Communities, and Local Economies" (EO 14072), references ecosystem services and emphasizes the importance of enlisting nature-based solutions to fight climate change, including the call for reporting nature-based solution opportunities to the National Climate Change Task Force (White House, 2022). Finally, at the time this article was submitted, the US Office of Information and Regulatory Affairs and the Office of Management and Budget released for public comment, "Guidance for Assessing Changes in Environmental and Ecosystem Services in Benefit-Cost Analysis" to assist US Federal agencies specifically in developing their regulatory impact analyses, policy, and program alternatives to include ecosystem services. While this is focused on a US federal nexus, they recognize that the guidance may also be relevant to other rule types "likely to have some ecosystem service effects include rules affecting contaminated site cleanup, financial

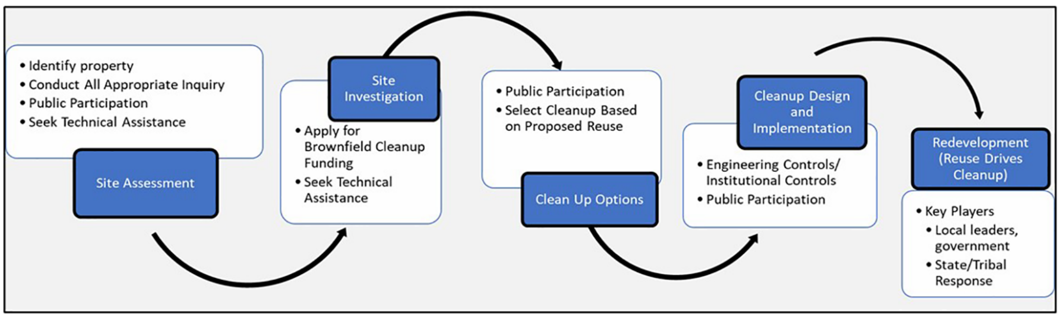

FIGURE 1
Brownfield cleanup process.

assistance, trade, fees, royalties, quotas, or credits, among others" (US OIRA and US OMB, 2023). Taken together, these policy tools and initiatives provide conceptual guidance to link brownfields revitalization with goals of enhancing multiple ecosystem services.

2.3 Public engagement

One challenge during the redevelopment process involves connecting brownfield redevelopment efforts to the larger community (stakeholders) in working to achieve goals which provide multiple societal benefits, such as public health and environmental protection, creation of jobs, public safety, and city revitalization (McCarthy, 2002). Historically, brownfields efforts focused primarily on providing incentive for developers as opposed to community-centered developments (Pippin, 2008). Community involvement in brownfields projects can promote the goals of revitalization, sustainable development, and smart growth. For example, the New Jersey Brownfields Development Area program recognizes that brownfield remediation should take place with community involvement (New Jersey, 2023). This program, established in 2002, requires state agencies, including the New Jersey Department of Environmental Protection, to work with local communities near brownfield sites to help with design and implementation of remediation plans. There may be local, regional, or state-relevant rules for community involvement in community planning efforts. There are also additional rules for community engagement for community planning responses to physical, social, economic, or governmental impacts by the actions of the Department of Defense (DoD) (24 CFR § 570.401, 1994).

The involvement of a community is crucial to a site's redevelopment, especially for addressing the community's needs and desires for the space. Often, the community starts off being involved and interested in a project, but as time progresses public engagement has the potential to diminish unless the project is large enough to have "public actor facilitation, i.e., representatives from public entities devoted time and energy to overcome barriers and complete the redevelopment." (Yount and Meyer, 1999). Early involvement with the community can help create an understanding of the process to improve buy-in and avoid community objections and litigation. When engaging in the community, using a common language has become an important strategy when talking to citizens from various backgrounds. Without having a common vocabulary, confusion can occur between local community members and the practitioners leading brownfields revitalization. All of these strategies are compatible with, and foundational for, consideration of design elements that add environmental benefits to a redevelopment effort. Specifically, early engagement with the community on the vision of a redevelopment creates the opportunity to identify elements such as green infrastructure that can then be incorporated into plans.

3 Elements of ecosystem services relevant to brownfield cleanups

3.1 Overview of ecosystem services

Considering the value of ecosystem services in decision-making improves the way resources are managed to benefit the community environmentally, economically, and socially, without negatively impacting essential components of the natural ecological community that may be present. In general, ecosystem services can typically be categorized by four main types: provisioning, regulatory, supporting, and cultural (Millennium Ecosystem Assessment, 2005). Provisioning services maintain the supply of natural products such as fuel, food, timber, water, and soil. An example in a brownfield cleanup context is the creation of a community garden (where appropriate). While provisioning deals with natural products, regulatory services filter pollutants to help water and air quality. Supporting services maintains both provisioning and regulatory services to preserve healthy habitats in both species and genetic diversity. An example in a brownfield cleanup context is the creation of habitat to support pollinator services. Finally, cultural services are intangible benefits of nature, such as spiritual and psychological benefits that include outdoor recreational activities (Holzman, 2012). An example in a brownfield cleanup context is the creation of greenspaces or community parks.

We conducted a non-exhaustive literature survey to identify a suite of nature-based solution design elements that contained resultant ecosystem services benefits. An example of common brownfield redevelopment elements, grouped into major categories of community garden, green infrastructure, greenspace, native plants, outdoor classroom opportunities, and educational signage, resulting in examples of environmental benefits is shown in Table 1 (Seybr and Lewis, 2008; Rall et al., 2015; Chowdhury et al., 2020). Community gardens can provide a source of food but cannot be established until soil testing demonstrates successful contaminant removal. Green infrastructure is used to help with stormwater management; however, local site conditions may favor routing water around a site, rather than through it. Other stormwater management features may include bioswales, rainwater harvesting, permeable pavements, or green roofs. Green roofs and green walls can provide heat attenuation and air cleaning benefits. Rain gardens and native plants can provide wildlife habitat as well as pollinator benefits. Education benefits can be provided through environmental signage and using spaces for classroom opportunities.

A number of greenspace features (e.g., community parks, green corridors, playgrounds, walking trails, and waterfront access) can provide myriad recreational benefits. With ongoing global growth and complexity of urban areas, the pressure to develop open green spaces within cities is increasing (Washbourne et al., 2020). By implementing ecological restoration of these contaminated sites (also referred to as eco-revitalization; US EPA, 2009), this recovery returns lost ecological function to previous environmental benefits.

TABLE 1 Examples of common nature-based solutions, often called design elements, and the associated ecosystem services and general timeline to achieve benefits (taken from Seybr and Lewis, 2008; Rall et al., 2015; Chowdhury et al., 2020).

Nature-Based Solutions (Design Elements)	Example Ecosystem Services	Timeline (Years)
Community Garden	Food production	1-3
Green Infrastructure	Stormwater & flood control	1+
Bioswales	Stormwater & flood control	1
Green Roofs	Stormwater & flood control Temperature regulation	2-5
Permeable Pavements	Flood protection	Immediate
Rain Gardens & Rainwater Harvesting	Wildlife habitat Stormwater & flood control	Immediate
Greenspace[1]	People accessing nature	1+
Community Park	Recreation benefits	Immediate
Green Corridors	Noise buffering Wildlife habitat	1+
Playground	Recreation benefits	Immediate
Walking Trails	Health and Recreation benefits	Immediate
Waterfront Access	Recreation benefit	Immediate
Native Plants	Pollination benefits	1+
Outdoor Classroom	Environmental education	Immediate
Educational Signage	Environmental education	Immediate

For examples of brownfields revitalization that successfully incorporated ecosystem services elements, see Table 3.

The use of greenspace and green infrastructure on brownfield land is an important mechanism for restoring sites, especially in the surrounding urban environment. Developing greenspace and green infrastructure can increase property value in and improve the quality of life of the surrounding community (Amati and Taylor, 2010).

3.2 Examples

Environmental benefits can be realized across a range of contaminants depending on the conditions of the site (Table 2). Depending on the end goal of the remediation process, the amount of cleanup required varies.

Examples of brownfield cleanup elements with environmental benefits can be seen in a variety of ways (Table 3). The authors identified three examples to described in more detail. Each example was reviewed by at least two authors to identify the environmental benefits elements described below.

The Stone Creek Tipple Site in Pennington, VA was once a mine-scarred land that was causing environmental and economic problems. This site was cleaned up and revitalized by removing the coal deposits; once the deposits were removed, two feet of soil was

TABLE 2 Examples of land use changes after brownfield cleanup of different types of contaminants and hazardous materials.

Example of Land Use Changes After Cleanup	Types of Contaminants & Hazardous Materials Remediated
The rails-to-trails project in Brea (CA) created 4.5 miles of bike and pedestrian trails[2]	Arsenic
Cleanup and rehabilitation of the Ball Park in McGill (NV)[2]	Asbestos
An abandoned urban lot is now the Emerson Street Garden in Portland (OR)[3]	Lead
5-acre cleanup along Spicket River (Lawrence, MA) turned into suite of environmental benefits[4]	Mercury
Redevelopment of former gas stations to create greenspace gateways into towns across Colorado[5]	Petroleum and Hydrocarbons
Riverbend Park remediation resulted in recreational benefits (Medford, MA)[6]	Polycyclic Aromatic Hydrocarbons (PAHs)
Turned a burn dump into a 9-acre Cooley Landing Park (East Palo Alto, CA) with native plants and grasses[2]	Polychlorinated Biphenyls (PCBs)
After understanding former property use made decision to turn into a garden (Manhattan, KS)[7]	Pesticides/Herbicides

Each case study reference (see footnotes) was reviewed by at least two authors to identify the environmental benefits elements listed in the left column.

1 Note other design elements in this table are also greenspaces.

2 https://www.epa.gov/sites/default/files/2015-10/documents/epa_oblr_successstory_region9_openspace_v2_508.pdf. Accessed January 21, 2024.

3 https://www.epa.gov/sites/default/files/2015-09/documents/bf-ss-emerson-street-032911.pdf. Accessed January 21, 2024.

4 https://www.epa.gov/sites/default/files/2015-09/documents/bf_ss_gw_lawrence_urban_waters_033111_web.pdf. Accessed January 21, 2024.

5 https://neiwpcc.org/wp-content/uploads/2020/06/FINAL_LUSTLine-87_Web.pdf. Accessed January 21, 2024.

6 https://medfordenergy.org/gogreen/brownfields/. Accessed January 21, 2024.

7 https://www.gardeningonbrownfields.org/docs/MF3096 Historical Property Usage and Implications 2017 update.pdf. Accessed January 21, 2024.

added. The transformation continued by seeding the land with native plants and stream bioengineering. The Pennington community can now enjoy trails, learning stations, and recycled material benches throughout this once contaminated land (Figure 2).

At a former abandoned Hi-Tech gas station in Brandywine Village (Wilmington, DE) the community was involved with the redevelopment process (as seen in Table 3). A permeable parking lot was constructed from previous paving material which enabled water to collect in piping under the parking lot from where it is transported to a bioswale. The project put peat moss and sand below the bioswale and parking lot to help absorb any contaminants that may be transported from the runoff.

TABLE 3 Examples of brownfield cleanup efforts that included design elements to create or enhance ecosystem services.

Location	Previous Land Use	Current Land Use	Ecosystem Services
Pennington Gap, VA	Stone Creek Tipple Site Coal mine[8]	Community park & outdoor classroom	Enhancing wildlife habitat; Stormwater and flood control; Recreational benefits; Pollinator benefits; Environmental education; Access to nature
Wilmington, DE	Brandywine Village Abandoned Hi-Tech gas station[9]	Greenspace (permeable parking lot)	Stormwater & flood control
Tahoe Vista, CA	Snow Creek Stream Environment Zone (SEZ) project[10]	Restored wetlands	Recreational benefits; Environmental education; Access to nature; Climate change resiliency
Palmerton, PA	Palmerton Zinc Pile[11]	450-acres of Native Prairie & Lehigh Gap Nature Center	Pollinator benefits; Environmental Education; Recreational benefits
Town of Coventry, RI	Former dumping ground[12]	20-acre Sandy Acres Recreation Area	Enhancing wildlife habitat; Stormwater and flood control; Recreational benefits
Crab Orchard, KY	Lincoln Co. Scrap Metal[13]	Public park	Walking trails; Recreation benefits
Tillamook County, OR	Veneer Mill[14]	Protected wetland	Wildlife habitat; Stormwater and flood control
Lake Tahoe, CA	Concrete Plant[15]	3-acre parcel of land with native habitat	Enhancing wildlife habitat; Access to nature
Brea, CA	Abandoned Union Pacific Railroad[16]	Multi-use trail	Access to nature; Environmental education; Recreational benefits
Fitchburg, MA	Rubber Factory[17]	Riverfront Park	Enhancing wildlife habitat; Stormwater & flood control; Recreational benefits

Each case study reference (see footnotes) was reviewed by at least two authors to identify the ecosystem services elements listed in the right column. For a list of common environmental benefits/ecosystem services in brownfield cleanup design, see Table 1.

The Snow Creek Wetlands restoration project in Tahoe Vista, CA, was a brownfields site that required cleanup and focused on features that provided ecosystem services, community benefits, and citizen engagement (Schuster et al., 2014). The 3.5-acre site is a filled-in wetland that used to be a former concrete plant site (Figure 3). With its location adjacent to a tributary of Lake Tahoe and close to the edge of the lake, the project team wanted to do more than just remediate the concrete material, address high pH in the soil, and remove the hydrocarbon-contaminated fill. The multi-stakeholder team was interested in environmental benefits of water quality improvements, access to greenspace, and improvement in aesthetics. The stakeholder-driven design process identified additional environmental benefits, including following the Placer County Low Impact Development Guidebook (Placer County, 2012) in designing restoration of the stream zone and upland habitat, establishing a multi-use path that provided access to nature, and installation of environmental education signage (Figure 3). Land revitalization in this project aimed to restore hydrology and create a buffer for existing

8 https://www.njit.edu/tab/sites/njit.edu.tab/files/stone_creek_outdoor_classroom_and_community_park.pdf. Accessed January 21, 2024.

9 https://www.njit.edu/sites/njit.edu.tab/files/de-wilmington.pdf. Accessed January 21, 2024.

10 https://www.placer.ca.gov/1657/Snow-Creek-Stream-Environment-Zone-Resto. Accessed January 21, 2024.

11 https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Cleanup&id=0300624#bkground. Accessed January 21, 2024.

12 https://www.epa.gov/sites/default/files/2016-01/documents/epa_oblr_successstory_sandyacres_v5_508.pdf. Accessed January 21, 2024.

13 https://19january2017snapshot.epa.gov/land-revitalization/lincoln-co-scrap-metal-crab-orchard-kentucky.html. Accessed January 21, 2024.

14 https://www.epa.gov/sites/default/files/2019-12/documents/going_with_the_flow_to_prevent_flooding.pdf. Accessed January 21, 2024.

15 https://www.epa.gov/sites/default/files/2015-10/documents/epa_oblr_successstory_region9_openspace_v2_508.pdf. Accessed January 21, 2024.

16 https://www.ci.brea.ca.us/791/The-Tracks-at-Brea-Trail. Accessed January 21, 2024.

17 https://archive.epa.gov/region1/brownfields/web/html/fitchburg_hrf_agp.html. Accessed January 21, 2024.

FIGURE 2
Stone Creek Tipple Site before (left) and after (right) cleanup. Photo credits: Virginia Department of Environmental Protection.

FIGURE 3
Snow Creek Wetlands restoration project before (left) and after (middle, right) cleanup. Photo credits: Kansas McGahan (left) and Placer County (middle, right).

environmentally sensitive areas and nearby residential neighborhoods. The team used the infrastructure-oriented Envision™ Sustainability Rating Tool (Institute for Sustainable Infrastructure, 2023) and emphasized sustainability practices, including working to reuse and repurpose existing site materials, consideration of climate change resiliency in the design process, the use of extensive stakeholder engagement, community involvement through educational outreach, and consensus-driven decision-making.

4 Tools and resources to enhance multiple benefits in brownfield cleanups

Multiple decision support tools and frameworks have been created for analysis of environmental benefits for different decision-making contexts. In a brownfield cleanup context, decision support tools can be used to overcome challenges among different stakeholder values and goals and to maintain interest in the revitalization effort over time. We conducted a non-exhaustive survey for "ecosystem services" and "environmental benefits" tools potentially useful for one or more steps in a generic brownfields cleanup process. For brownfields, example decision support tools that may be useful to a community include the Vision-to-Action tool, Timbre Brownfield Prioritization Tool, the Envision Sustainability Rating Tool, EnviroAtlas, the Eco-Health Relationship Browser, and the Final Ecosystem Goods and Services (FEGS) Scoping Tool. Each have been developed to address the different aspects of environmental decision-making processes. We note that there may be other applicable tools for consideration.

The Vision-to-Action tool[18] is used by the US EPA to aid the stakeholder community. This tool is designed to inspire community members to visualize what they value, how they would like to see their community change, and to bring those visualizations into reality (US EPA, 2022). The tool's process brings together ideas from multiple individuals/stakeholders graphically to try to form

18 https://www.epa.gov/brownfields/brownfields-vision-action-tool. Accessed January 21, 2024.

common themes that lend themselves to dedicated decisions/actions by community leaders. The overview of the Vision-to-Action tool includes several examples of community and waterfront revitalization (US EPA, 2022).

The Timbre Brownfield Prioritization Tool[19] is used by stakeholders to identify which brownfield sites should be considered for redevelopment. The tool prioritizes the success factors determined by the stakeholder engagement and a site's redevelopment potential. The Timbre Brownfield Prioritization Tool was tested on 235 European brownfield sites across the Czech Republic, Germany, and Poland (Pizzol et al., 2016). The authors concluded that the tool was effective in providing a starting point for users who need to collect detailed information for pre-selecting those sites that had the highest potential for redevelopment. They also concluded that during pre-selection of brownfield sites the tool was useful in identifying agricultural brownfields with the highest redevelopment potential based on pre-determined criteria. Overall, the Timbre Brownfield Prioritization Tool provides a better understanding of the different variables when choosing a site based off the relevant parameters in line with the user's needs.

The Envision Sustainability Rating Tool[20] is a tool for identifying sustainable elements used during planning, design, and construction of infrastructure projects (Institute for Sustainable Infrastructure, 2023). Elements are grouped into five categories (quality of life, leadership, resource allocation, natural world, and climate and risk). The rating system, developed by The Institute for Sustainable Infrastructure (ISI), includes a self-assessment, verification, and award recognition components. The Snow Creek Wetlands restoration project described above used the Envision Sustainability Rating Tool.

The EnviroAtlas[21] is an interactive, web-based map resource, providing over over 400 map layers layers incorporating seven broad datasets to organize information on potential environmental benefits. This tool can be used to help screen and evaluate a community's vulnerabilities as well as assets which can give an indication on how to redevelop a brownfield site (US EPA, 2023a). Recently, the EnviroAtlas released a set of brownfield-relevant, curated map layers, allowing users to view and assess brownfield information for any location in the conterminous United States.

The Eco-Health Relationship Browser[22] is an interactive tool that provides information connecting ecosystems and the benefits they provide to how those benefits affect human health and the community (Jackson et al., 2013). This tool has six broad urban ecosystem categories including: water hazard mitigation, recreation and physical activity, heat hazard mitigation, water quality, air quality, and aesthetics and engagement with nature. Each of these categories can be explored to learn about research demonstrating direct human health connections.

The Final Ecosystem Goods and Services Scoping Tool[23] is a tool for decision makers early in the project stage. The FEGS Scoping Tool prioritizes stakeholders, environmental attributes, and beneficiaries in the restoration context. By identifying the more relevant ecosystem services, the decision-making process will make restoration in the community more effective. The intended audience for this approach includes communities, private and public sectors, non-profits, and individuals.

An evaluation of environmental benefits can include examining loss of benefits resulting from the impacts of the brownfield site, neighboring environmental benefits that could be enhanced by cleanup, or identification of potential future environmental benefits as part of brownfield cleanup and reuse design. An organizational way to explore these resources is to crosswalk the generic brownfields cleanup phases (Figure 1) with potential tools and resources as outlined in Table 4. For early cleanup phases of environmental site assessment and site investigation, a primary consideration is the evaluation of a community's vulnerabilities and assets along with relevant environmental elements that may be involved in a given brownfield cleanup decision. Consideration of environmental benefits can also be incorporated into a community's future visioning of cleanup options.

5 Discussion and summary

Nature-based solutions are actions to protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges, simultaneously providing benefits for people and the environment. Concepts from the field of ecosystem services, benefits from nature, can be useful for communities and decision-makers to establish priorities for brownfield development projects which identify and prioritize linkages between the environment and human welfare. This article introduced concepts of enhancing environmental benefits in brownfield sites, explored examples of environmental benefits achieved from brownfield cleanups, and discussed how to consider these types of benefits into brownfield planning efforts.

Decision-makers can use recent policy tools to encourage brownfields revitalization that helps to combat the climate crisis, apply nature-based solutions, and enhance ecosystem services. Operationalizing the concepts and tools presented in this study will increase the number of resources available to communities to help them design and implement their brownfield reuse goal that may include environmental benefits. As more brownfield applications use the tools described here, these decision support

19 http://www.timbre-project.eu/tl_files/timbre/Intern/4%20Work%20Packages/WP3/Presentations&Manuals/Brochure_TIMBRE_Prioritisation_Tool.pdf. Accessed January 21, 2024.

20 https://sustainableinfrastructure.org/envision/use-envision/. Accessed January 21, 2024.

21 https://www.epa.gov/enviroatlas/enviroatlas-brownfields. Accessed January 21, 2024.

22 https://www.epa.gov/enviroatlas/enviroatlas-eco-health-relationship-browser. Accessed January 21, 2024.

23 https://www.epa.gov/eco-research/final-ecosystem-goods-and-services-fegs-scoping-tool. Accessed January 21, 2024.

TABLE 4 Cross-walking different brownfield cleanup phases with tools and other considerations for a community to identify elements with environmental benefits.

Cleanup Phase	Description	Tools & Considerations
Environmental Site Assessment	Investigate specific hazards that are present to achieve a better understanding of how to approach the cleanup	When developing cleanup and reuse goals, evaluate a community's vulnerabilities and assets, including environmental elements. Example resources: The Vision-to-Action tool; Timbre Brownfield Prioritization Tool; Envision Sustainability Rating Tool; EnviroAtlas; and Eco-Health Relationship Browser
Site Investigation	Identify funding sources	
Cleanup Options	Determine level of cleanup and type of project elements	Consider environmental benefits when a community develops a vision for a site's reuse to inform options for project elements and options. Example resources: EnviroAtlas; FEGS Scoping Tool; Envision Sustainability Rating Tool
Cleanup Design and Implementation	Type of cleanup and anticipated future reuse plans defines engineering and institutional controls	
Redevelopment Phase	Integrates site assessments and incorporate neighborhood-relevant features to address the community concerns for the reuse vision	Example resources: The Vision-to-Action tool; Envision Sustainability Rating Tool

tools can be better refined and translated for use in brownfield applications in future efforts.

While Section 2.1 describes the generic cleanup process for United States brownfield sites, our study is also relevant to cleanups elsewhere. As of 2018, there were approximately 2.8 million potentially contaminated sites in the European Union (Pérez and Eugenio, 2018), for which recent efforts have focused on mechanisms such as the pending European Soil Monitoring Law (COM, 2021) to establish connections between site cleanups and ecosystem services. The concepts described here can be used to enhance other efforts such as the European Union's GREEN SURGE effort, looking to connect urban green spaces, green infrastructure, and ecosystem services (Rall et al., 2015) and environmental elements of low impact design for brownfields cleanup in New Zealand (Seybr and Lewis, 2008).

Future activities should focus on communication and operationalizing these concepts, the application of tools and other resources in on-the-ground applications, and documenting and communicating successful examples. Developing a library of examples has been successfully used in green and sustainable remediation efforts and can result in extending these ecosystem services concepts to a wider audience, including natural and social scientists, communities, and environmental decision-makers. Finally, over time, a larger suite of "success stories" can be documented and shared by including consideration of environmental benefits in brownfield cleanups.

Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions

MH: Writing – original draft, Writing – review & editing. BM: Writing – original draft, Writing – review & editing. KG: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author disclaimer

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Connecting stakeholder priorities and desired environmental attributes for wetland restoration using ecosystem services and a heat map analysis for communications

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Framing ecological restoration and monitoring goals from a human benefits perspective (i.e., ecosystem services) can help inform restoration planners, surrounding communities, and relevant stakeholders about the direct benefits they may obtain from a specific restoration project. We used a case study of tidal wetland restoration in the Tillamook River watershed in Oregon, USA, to demonstrate how to identify and integrate community stakeholders/beneficiaries and the environmental attributes they use to inform the design of and enhance environmental benefits from ecological restoration. Using the U.S. Environmental Protection Agency's Final Ecosystem Goods and Services (FEGS) Scoping Tool, we quantify the types of ecosystem services of greatest common value to stakeholders/beneficiaries that lead to desired benefits that contribute to their well-being in the context of planned uses that can be incorporated into the restoration project. This case study identified priority stakeholders, beneficiaries, and environmental attributes of interest to inform restoration goal selection. This novel decision context application of the FEGS Scoping Tool also included an effort focused on how to communicate the connections between stakeholders, and the environmental attributes of greatest interest to them using heat maps.

KEYWORDS

ecosystem services, tidal wetlands, restoration, stakeholders, nature's benefits, decision-making

Abbreviations: EPA, U.S. Environmental Protection Agency; ES, Ecosystem services; FEGS, Final Ecosystem Goods and Services; MCDA, Multi-criteria decision analysis; OWEB, Oregon Watershed Enhancement Board; TEP, Tillamook Estuary Partnership; TRW, Tillamook River Wetlands.

1 Introduction

Ecosystem restoration is pursued for a variety of reasons, including improving the condition of the environment, and increasing the benefits for people who use, rely on, or care about the restored environment (ecosystem services; ES). Recognition of the need and efforts to consider and integrate ecosystem services into environmental decision-making has become an increasingly integral aspect of ecosystem-based management (Olander et al., 2018). As a result, funding for restoration projects increasingly incorporates design and justification for flows from the ecosystem to human well-being to leverage funding and stakeholder support (Jackson et al., 2022; Rossi et al., 2022).

A challenge with efforts to incorporate and quantify ES in restoration is that often, biophysical attributes of ecosystems are expressed as services without describing the full benefits to humans (DeWitt et al., 2020), or they measure economic values of end uses of ES (e.g., Russell et al., 2020). These approaches often leave out a large subset of possible ES that hold high cultural and social value (Chan et al., 2012). Studies have shown that when residents are asked to measure the value of nearby natural spaces, they highly value social and cultural benefits without attaching monetary values to those benefits (Pedersen et al., 2019).

Specifically, Final Ecosystem Goods and Services (FEGS) are those aspects of the environment that are directly enjoyed, used, or consumed by humans (Boyd and Banzhaf, 2007). They are specified as *final* because of the *direct* benefit they provide to humans (Boyd and Banzhaf, 2007; Landers and Nahlik, 2013; DeWitt et al., 2020). The consideration of FEGS can include a focus on those services that hold high cultural and social value.

With many constraints in ecological restorations, and with the expansive array of ES and benefits to humans, prioritizing which services to integrate into restoration can be challenging for managers. One approach to address these challenges is to conduct an analysis of ES priorities from related restoration projects locally, regionally, nationally, or by type of organization (e.g., Yee et al., 2019; Jackson et al., 2024) and develop a list of potential services of interest that can be considered for the local restoration context. This is especially useful when supporting literature is robust. Another approach is to determine what ES are of greatest interest to stakeholders and the general community (Chan et al., 2012; DeWitt et al., 2020; Sharpe et al., 2020).

The U.S. Environmental Protection Agency's (EPA) National Ecosystem Services Classification System Plus (NESCS Plus; Newcomer-Johnson et al., 2020), uses three components to classify ES: 1) an environment type (i.e., where the service is produced); 2) the beneficiary or user (i.e., the role(s) people have when caring about the service); and 3) an ecological end product (i.e., the attribute of nature from which the benefit is derived). The FEGS Scoping tool, using NESCS Plus as its foundation, offers a way to identify priority interests for a given decision context (here, initial stages in restoration planning) in a transparent manner. This tool is designed to avoid conflicts by clearly articulating what stakeholder interests are, finding shared interests where they may or may not be obvious, and communicating what environmental attributes are relevant to support those interests (Sharpe et al., 2020). The FEGS Scoping tool uses a tiered multi-criteria decision analysis (MCDA) approach to highlight priorities of a decision. The tool uses MCDA to rank alternatives by the sum of weighted criteria. The tool's objectives are to prioritize stakeholders, prioritize beneficiaries, and prioritize environmental attributes, with each step feeding into the next. For details about the tool, including the underlying methodology, the reader is referred to Sharpe et al. (2020) and Sharpe (2021).

This case study of a wetland restoration project in Tillamook Bay, Oregon is a demonstration of how to use an ES classification system that incorporates a wide array of environmental benefits (Newcomer-Johnson et al., 2020) and a tool that facilitates a systematic identification of stakeholder interests associated with specific environmental decision contexts (Sharpe et al., 2020). The objective of this study was to provide the Tillamook Estuaries Partnership (TEP) team with a structured approach for identifying stakeholder interests and incorporating those ES relevant to their interests into restoration goals. This was done by applying the FEGS Scoping tool to the final decisions on the restoration of the tidal wetland of the Tillamook river. While the results are specific for the Tillamook Bay restoration effort, the approaches and application of the FEGS Scoping Tool are applicable to other decision contexts.

1.1 Case study site

The Tillamook Bay basin, located along the coast of northern Oregon, is inextricably linked to the natural environment through fisheries, forestry, agriculture (particularly dairy farming), and nature-based recreation and tourism (Tillamook Estuary Partnership (TEP), 2019) . Legacy forestry and farming practices degraded or transformed many of the wetlands in the watershed, and their loss has been associated with increased low-land flooding, reduced salmon populations, and degradation of water quality (Tillamook Estuary Partnership (TEP), 1999; Komar et al., 2004; Tillamook Estuary Partnership (TEP), 2019). Restoration of tidal wetlands is a priority of the Tillamook Estuaries Partnership, a National Estuaries Program site established in 1994, to improve water quality and wetlands habitats within Tillamook County (Tillamook Estuary Partnership (TEP), 1999, 2019).

The TEP is leading the restoration planning and implementation at a site called the Tillamook River Wetlands (TRW), a 73-acre site at mile three of the Tillamook River (Figure 1). The existing road infrastructure in the site experiences frequent flooding and thus often experiences damage and need for repairs. Historically, tidal wetlands around Tillamook, including within the TRW Restoration site, were significantly covered by Sitka Spruce (*Picea sitchensis*) swamp habitat (Brophy et al., 2019a). There was deforestation in the watersheds that feed into Tillamook Bay between 1931-1954 (Komar et al., 2004), including extensive loss of Sitka Spruce (Brophy, 2019). In the greater Tillamook Bay, an estimated 62.8% of tidal forest wetland and 63% of scrub shrub wetland still exists (Brophy, 2019). The TRW Restoration site has some forested wetland, specifically Sitka spruce remaining, a fraction of historical cover since the area was diked

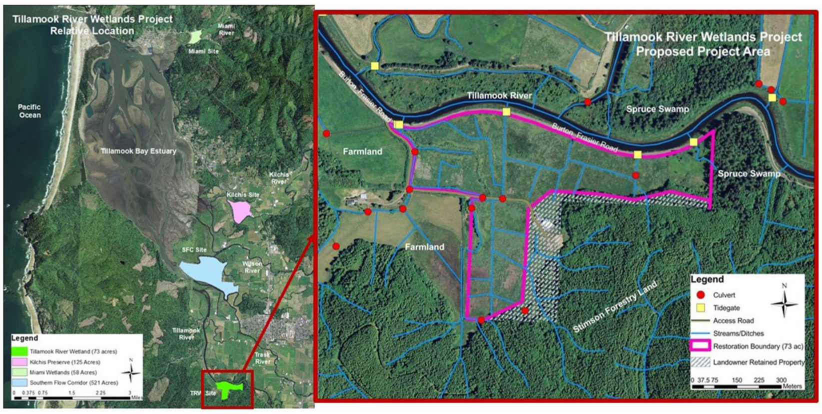

FIGURE 1
Tillamook Bay and several recent TEP restoration sites. The Tillamook River Wetlands restoration site, on the southern end of the bay is shown in more detail on the right, which shows the restoration boundary, streams and ditches, tide gates, and culverts. Outside the restoration site, the western side is mostly farmland, managed forest to the south, and spruce swamp to the east and northeast across the Tillamook River (Oregon Watershed Enhancement Board (OWEB), 2017).

and drained (Oregon Watershed Enhancement Board, (OWEB) 2017). The site was acquired in 2020 by the North Coast Land Conservancy (NCLC) as a perpetual conservation easement and to "help protect and restore healthy watersheds and natural habitats that support thriving communities and strong economies." (OWEB, n.d.). When acquired, the site consisted of palustrine emergent wetlands (86.6%), palustrine forested wetland (2.7%), and upland habitats (10.5%) (Oregon Watershed Enhancement Board, (OWEB) 2017). The tidal wetlands in Tillamook Bay are used by the federally threatened Oregon Coast Coho Salmon (*Oncorhynchus kisutch*) in addition to seven other salmonid species and 17 other known federally or state recognized species of concern (Oregon Watershed Enhancement Board, (OWEB) 2017). At the time of the study, the TRW partners were analyzing alternatives in the restoration design. The alternative analysis provided the county and private landowners with restoration alternatives that include consideration of climate change and infrastructure pressures (Tillamook Estuary Partnership (TEP), 2022).

For the TRW Restoration project, an increased trend in flooding events constitutes the major impetus for the need to consider restoration interventions. Currently, the site has a road that runs along the south bank of the Tillamook River, and several points of the road system flood 20-50 times a year. While supporting infrastructure has been installed (e.g., scour protection aprons between the road and river edge), those features are beginning to fail and there is significant deterioration of older road segments (Tillamook Estuary Partnership (TEP), 2022). Flood risk in Tillamook is increasing, and projections include increased erosion that could increase damages and costs to properties and structures (Komar et al., 2004; Oregon Department of Fish and Wildlife (ODFW), 2006; Brophy et al., 2019b). The TEP team recognized that there were multiple stakeholders for the TRW Restoration project with diverse benefits, and interests beyond the need to reduce and mitigate flooding.

The TRW Restoration managers and partners (Tillamook County Public Works, North Coast Land Conservancy, and Oregon Watershed Enhancement Board (OWEB)) are invested in incorporating stakeholder interests into project planning and implementation, and garnering project support from affected communities from the early planning stages. The TRW Restoration site, though rural, is surrounded by people with a variety of recreational and economic interests such as forestry, hunting, angling, farming, grazing, and boating (Gray, 2000). Studies have shown that coastal Oregon communities have experienced considerable demographic and economic changes. Overall, coastal areas have seen decreases in resource-based industries such as commercial fishing and timber, while personal incomes and employment associated with businesses serving tourism and retirees have increased (Gray, 2000; The Research Group, 2006; Ackerman et al., 2016). A study published in 2006 found that Tillamook still has a significant agricultural industry, 13.1% of total personal incomes, whereas tourism constitutes 3.8% of total personal incomes, lower than the coast-wide estimate of 5.6% of total incomes contributed by tourism. Oyster production in Tillamook Bay has decreased from an estimated 30,916 gallons in 1984 to 12,151 gallons in 2003 (The Research Group, 2006). Timber continues to be significant though the industry has been affected by a series of forest fires in Tillamook County from up until the 1950s (Gilden and Conway, 1999). An economic outlook by Gilden and Conway estimated that the timber would increase, and in 2006 was estimated to be 12.0% of Tillamook's total personal incomes (Gilden and Conway, 1999; The Research Group, 2006). By 2019, outdoor recreation was determined to be a significant economic sector in Tillamook County, with over $737 million spent to support recreational activities and visitors (Mojica et al., 2021).

Past restoration efforts in other Tillamook Bay watersheds have included holding stakeholder hearings to formulate and vote on preferred restoration alternatives recognizing disparate viewpoints of potential outcomes (Gregory and Wellman, 2001). For example, the impetus of a large restoration project in an adjacent watershed that feeds into Tillamook Bay, the Southern Flow Corridor, was a storm that resulted in millions of dollars of damages in 2006. The Southern Flow Corridor restoration projects had points of public contention during planning, thus was forestalled and forced into a third-party mediation (Levesque, 2013; Haeffner and Hellman, 2020). While the project was successful at decreasing flooding in adjacent areas, the importance of other ES and benefits (e.g., diverse recreation and education benefits noted as important to stakeholders) (Janousek et al., 2021; Shaw and Dundas, 2021) was not measured.

At the outset, TEP and its partners were identifying alternatives to analyze for restoring the TRW Restoration site (Tillamook Estuary Partnership (TEP), 2022). For this project, we applied the tool considering that some of the restoration facets would likely need to include reconstructing the tide channel, and either upgrading or removing the road. In removing the road, a road outside the site would also be upgraded to withstand more traffic.

2 Methods

The TEP team was interested in having a structured approach for identifying stakeholder interests, and reconciling possible conflicts, while identifying those ES needed to sustain stakeholder interests and can be incorporated into restoration goals. The results of our analysis might then be used to inform the development of nominal restoration goals for this site and frame forthcoming discussions with local stakeholders This case study used the extensively peer-reviewed, publicly available FEGS Scoping Tool (Sharpe, 2021) in collaboration with TEP restoration managers, who were interested in how best to engage stakeholders in the planning process. Oftentimes, there are distinct stakeholders who have clearly competing interests, obscuring whatever shared interests they may have, so the TEP restoration managers wanted to use the FEGS Scoping Tool to help find shared interests among a possibly wide range of collective interests. The FEGS Scoping Tool was used to take a comprehensive and structured approach to identify stakeholders and the ways they are, or could be, benefiting from the area being considered for restoration. The tool required managers to take a more deliberative approach towards considering stakeholders and benefits. This allowed managers to identify groups that might otherwise be overlooked, capture potential impacts that managers should be prepared to address during discussions with stakeholders, and identify groups that may not be aware that this effort will affect them.

We worked with the TEP restoration managers, using the steps and guidance of the FEGS Scoping Tool (see Sharpe et al., 2020 and Sharpe, 2021 for tool methodology), to define the decision context; to identify and prioritize stakeholders; to define the benefits that stakeholders were interested (beneficiaries); and to determine the environmental attributes for each beneficiary. The tool requires each criterion be scored for the decisions at hand, and that each stakeholder group be identified and evaluated toward each criterion. Secondly, the environmental benefits of each stakeholder group need to be identified. And third the environmental attributes needed to realize each type of benefit must be identified. Each step is guided by well-defined choices specified in lists within the software. Thus, the tool requires many data inputs, which were determined through interviews of two TEP restoration managers conducted by a team of four EPA researchers. This data input process was accomplished as a series of virtual meetings to discuss the project and walk through the tool. The FEGS Scoping Tool was used very early in the decision-making process to help inform the upcoming evaluation of engineering alternatives that could be made to existing tide gates, roads, and other infrastructure.

The FEGS Scoping Tool uses a tiered approach to MCDA using key criteria, explicitly evaluated by the people making the decision or using the tool, to prioritize stakeholder groups interests when evaluating alternatives and with limited resources (Sharpe, 2021). The TEP restoration managers requested a visual-communication tool output that could more explicitly connect the environmental attribute results back to individual stakeholder groups, and to individual beneficiary groups (Figure 2; Hernandez et al., 2022). The tool produces bar charts that indicate the relative prioritization for each of the stakeholders, beneficiaries, and environmental

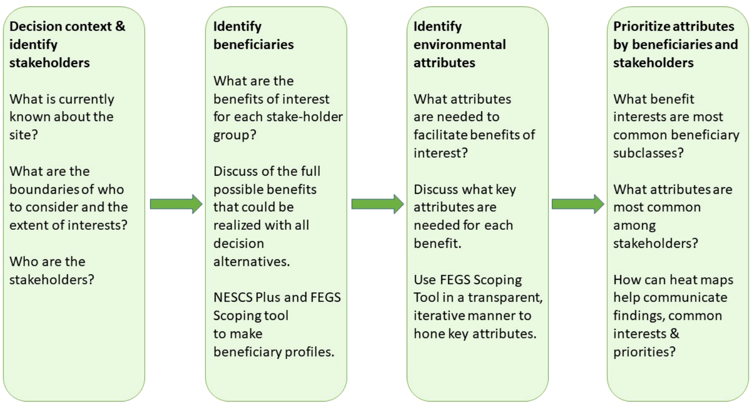

FIGURE 2
Conceptual diagram of the steps used to apply the FEGS Scoping Tool and other analyses for the Tillamook River Wetlands Restoration site.

attributes (Sharpe, 2021). Furthermore, we used the calculations built in the FEGS Scoping Tool software to do a crosswalk between the environmental attributes and the suite of stakeholder groups as identified by the TEP restoration managers. To do this, we populated the raw data from the tool into a simple spreadsheet, color-coding cells different shades depending on the value of a given cell relative to the overall range of results to develop a heat map for visually displaying results. Each step of using the FEGS Scoping Tool for this case study is described in the following four sections.

2.1 Decision context, identifying stakeholders

In the stakeholder prioritization step, the key decision criteria that the tool asks users to consider are: interest; influence; impact; urgency; proximity; economic interest; rights; fairness; and underrepresented/underserved populations (Sharpe et al., 2021). The decision context for this prioritization was clarified through discussions with the TEP restoration managers of what the impetus was for the land acquisition, the current knowledge of pressing hydrological issues at the site, the impacts to surrounding communities, and both current and likely stakeholder interests in connection to the site and restoration decisions and outcomes. Setting the decision context included defining the geographic bounds of adjacent areas and identifying stakeholders that would potentially be impacted by: 1) being near the restoration site boundaries; and 2) the uses associated with road access through the site given that a nearby road could be modified to replace the current road if the current road running through the site is removed.

The stakeholder prioritization criteria are weighted by the tool users or decision makers to transparently convey which criteria matter most to those using the tool and/or making the decisions when determining the relative priority of the stakeholder groups. Subsequently, each stakeholder is scored on those criteria according to what degree the stakeholder group met each criterion. The values recorded in these two initial steps propagate through the FEGS Scoping Tool analysis as the prioritized stakeholder groups affect the prioritization of beneficiaries and of the environmental attributes associated with the restoration of the TRW Restoration site (Sharpe et al., 2020; Sharpe, 2021).

The TEP restoration managers had completed some initial background information collection and restoration planning activities for site and surrounding areas, such as communicating with some key stakeholders before beginning the process of the FEGS Scoping Tool application. Their knowledge was instrumental in being able to identify and characterize the most likely stakeholder groups to consider and the benefits those stakeholders were seeking from the restoration site. In total, 15 stakeholder groups were identified (Table 1; Hernandez et al., 2022). Initial conversational meetings were held to discuss the site's current conditions, identifying stakeholder groups, and weighting the decision criteria

TABLE 1 Stakeholder groups for the Tillamook River Wetlands Restoration project and a brief description of who they represent.

Stakeholder	Description of the Group
NCLC Site Landowners	The North Coast Land Conservancy is a non-profit conservation organization. Primary landowners of the site. They require wetland restoration as part of the property acquisition.
TEP & Partners	The Tillamook Estuaries Partnership, and other organizations involved in facilitating the decision making, restoration implementation, and management/monitoring. (TEP helps steer project, with less say than landowners.)
Funders	Organizations that fund site acquisition and restoration interventions. Includes Oregon Watershed Enhancement Board, private donors.
Rural Resident Neighbors	Residents who live on adjacent properties and have direct access to Burton Fraser Road. Excludes the Tillamook Shooters Association.
Tillamook Shooters Association	Landowner that sold the property; owners of adjacent property with interest to create a hunting/gun club and who share wetland habitat with the site.
Industrial Timber Neighbors	Non-residential, for-profit timber growth forests in adjacent property lands. Potential decision outcomes may require additional small land acquisitions from them.
Industrial Dairy Neighbors	Adjacent dairy operators who may be directly impacted from decision outcome.
Commercial Community	Other commerce – fishing industry, aquaculture operators that stand to be impacted from downstream effects due to decision outcome. Rock quarry in the greater neighborhood uses Burton-Fraser Road occasionally; they are not expected to receive other direct ecological benefits from the site.
Dairy Community	Represents the influence and interests of the broader coalition of dairy operators/farmers and the dairy industry in Tillamook Bay.
Utilities	Added to consider roles of local cable and electricity providers who may have infrastructure in/near the site, although no services infrastructure was known to exist in the immediate restoration site at the time of discussion.
Commuters	Locals who use the roads in question on a frequent basis to commute to and from adjacent communities.
General Public	Any resident within the county who can comment on the decision process or comment on the transportation related decisions and [collectively] influence.
County Agencies	Public Works, planning commissions. Will be very involved in road maintenance and permitting and planning potential road infrastructure changes.
State Agencies	Includes Oregon Department of Fish and Wildlife. Have permitting roles with interests in recreation (angling, hunting, etc.) and conservation. There is interest in seeing research done at this site.
Federal Agencies	Includes the National Oceanic and Atmospheric Administration, the U.S. Fish and Wildlife Service, the U.S. Army Corps of Engineers. Overall, have permitting and management roles, comment on Clean Water Act regulations, with missions to sustainably manage natural resources for existence, current and future benefit/use.

from the perspective of the restoration managers. The restoration managers identified how each of the stakeholder groups met each of the decision criteria.

2.2 Identify beneficiaries

After stakeholder groups are identified and prioritized according to the decision context criteria, the FEGS Scoping Tool asks the user to characterize how each stakeholder group benefits from nature (i.e., identifying the beneficiary profile) according to the beneficiary classification defined in the NESCS Plus (Newcomer-Johnson et al., 2020). Each stakeholder group was segmented, by percentage, into the ways they benefit from nature (Figure 3).

Keeping in mind the ecological setting of the site, the decision context boundaries, geographic boundaries, and the interests of stakeholder groups, a beneficiary profile for each group was created to better understand the ways in which a group may be impacted as a result of changes to the TRW Restoration site. The ways in which each group interacts with the ecological setting and geographic boundary informs what nature-based benefits may already be produced by the site or are of interest in being addressed through the restoration process. Some benefits are used or enjoyed primarily at the site (e.g., viewing wildlife or minimizing flood damage) whereas other benefits are realized over an area larger than the site (i.e., vistas of wetland habitat, production of game fish) (Ringold et al., 2013). This variability in location where ES are enjoyed relative to where they are produced affects the range of types of beneficiaries that will be affected by restoration of the TRW Restoration site.

2.3 Identify environmental attributes

The last step regarding the inputs in the FEGS Scoping Tool was to identify the environmental attributes necessary for each beneficiary to receive the benefits they value in the context of the decision and location of the site. The environmental attribute categories and subcategories in the FEGS Scoping Tool guidance follow the suite of categories and definitions from the NESCS Plus (Newcomer-Johnson et al., 2020).

The environmental attributes step was approached by identifying what individual attributes are needed to sustain the interests and uses of the beneficiaries at the site for the decision context. Some benefits may be used or enjoyed within a site's boundaries (e.g., wildlife viewing, extraction of timber) whereas other benefits are produced over an area larger than the site (e.g., vistas of wetland habitat, production of game fish) (Ringold et al., 2013). While a beneficiary may care about multiple attributes of the environment within a restoration site, when assuming a specific beneficiary role, we made a concerted effort to consider the most relevant biophysical attributes (such as flooding and water quality) needed to directly use, consume, or appreciate the environment in order to fulfill the specific benefit for the beneficiary role.

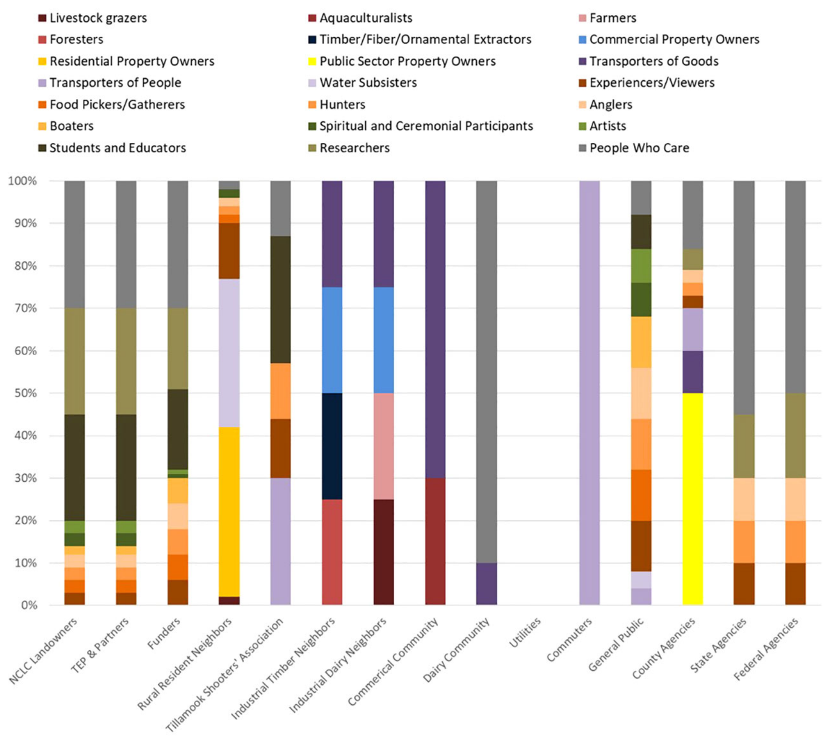

FIGURE 3
Beneficiary distribution for each stakeholder group; Utilities (local utility companies) were a stakeholder group that was considered to likely have no beneficiary interests at the site. (Reproduced from Hernandez et al., 2022).

2.4 Prioritize beneficiaries and attributes

The FEGS Scoping Tool uses a tiered version of the multi-criteria decision approach, known as ranking the alternatives, on the sum of weighted criteria (Sharpe et al., 2020; Sharpe, 2021). In the first step, the decision criteria are weighted and used to score the stakeholder groups. The combination of weighting and scores results in a prioritization value for each group. This result is then used as the weight in the second step. The result of the second step, the prioritization value of each beneficiary group, is used as the weight in the third step. This means that, in the raw data of the weights and scores, it is possible to show the relative priority of the attributes for each stakeholder group, even though it is not an explicit tool output. This analysis allowed managers to see common attributes of interest across stakeholder groups explicitly, in addition to the tool output display of common attributes of interest across beneficiary groups. This was done externally to the tool itself, using the same inputs as the tool.

3 Results

Given that the FEGS Scoping Tool focuses on information to help evaluate: (1) what benefits stakeholder groups are interested in for the site; and (2) what environmental attributes are needed to realize those benefits, results below include both qualitative and quantitative information. It is important to note that this study primarily focuses on the human-dimension elements of the early phases of planning a wetland restoration project, and the TEP restoration managers were interested in both qualitative and quantitative outcomes of this study.

3.1 Decision context

The decision context was set based on the restoration managers' knowledge at the time of discussing and recording the FEGS Scoping Tool inputs, and their expected next steps in the restoration planning process. The criteria do not have to be considered independently of one another. For the TRW Restoration project, the most important criteria were level of influence and rights, each of which were equally weighted. In total, eight criteria had scores greater than 50 as determined by the restoration managers (Table 2). The decision makers or tool users (in this case, the users were the restoration managers, with discussion with EPA researchers) determine which of the decision criteria are most meaningful to them when distinguishing among priorities and the stakeholder groups (Sharpe et al., 2020, 2021; Hernandez et al., 2022). Though the criteria reflect the values set by the tool users, the tool makes this step transparent for valuing the criteria that are key to stakeholder and decision analyses (Belton and Stewart, 2002; Gregory et al., 2012; Sharpe et al., 2021).

When considering the influence criterion and establishing weights, the TEP restoration managers felt that the authority to approve or strike down restoration design and interventions was meaningful for distinguishing among stakeholder groups. Some stakeholders may have significant informal influence on other stakeholders, thereby affecting decisions about the design and implementation of the project. The TEP restoration managers felt those groups with the ability to block or significantly influence plans should be prioritized. The critical effect that an authority could have on the project itself led to weighting influence as one of the most important criteria.

TABLE 2 Weights assigned to each criterion to determine the decision context.

Criterion	Weight
Level of **Influence**	100
Rights	100
Magnitude and Probability of **Impact**	90
Proximity	90
Economic Interest	70
Urgency and Temporal Immediacy	65
Level of **Interest**	50
Fairness	50
Underrepresented & Underserved Populations	10

Weights can range 0-100; criteria with a weight of 100 are the most important, and other criteria are subsequently weighted relative to those. Bolded word(s) for each criterion correspond to how each is summarized in Figure 4.

Although TEP restoration managers initially assigned 100% to the importance of rights (Table 2), groups that have property, legal, property, or formal user rights in the decision making and outcome of the restoration needed to be distinguished and given higher weight than through other criteria. It is important to note that the FEGS Scoping Tool can be used in an iterative fashion, allowing managers the opportunity to examine different weighing overall. Some stakeholders have the authority or legal standing to approve or block the restoration design or implementation. The first alternative may include major structural improvements to Burton-Fraser Road, which would create a detour north through Tillamook or south through Eckloff road, which would cause significant traffic delays for a minimum of two years during construction. The second alternative includes removing a portion of the current Burton-Fraser Road and upgrading Eckloff road, which would cause traffic delays while Eckloff road is under construction but would later cause minimal impact to traffic. However, current conditions of the Burton-Fraser Road are deteriorating bank protections, and portions of the road frequently flood during very high tides, naturally delaying commuter traffic (Tillamook Estuary Partnership (TEP), 2022). Both could potentially impact several stakeholder groups. Thus, impact was weighted highly (90%; Table 2) to elevate the importance of the impact to stakeholders who frequent roads in the area.

The TEP restoration managers wanted to consider how people who are nearest to the site will be affected by modifications to Burton-Fraser Road. They were also concerned about how restoration and future uses of the TRW property may impact surrounding property values, businesses, etc. Hence, the criterion for proximity weighted highly and at the same weight as magnitude and probability of impact.

There was no expected significant direct economic impact from the possible removal of a section of Burton-Fraser Road adjacent to the TRW Restoration site. An adjacent farm would be most affected by the road change, but the expected impact would be small. A road closure would cause commuters and tourists to take a slightly longer route, but the county would be relieved of the expense to frequently maintain and repair the road. Modifications to the land use might affect neighboring property values or land uses, although whether the likely net effect of TRW Restoration would result in an increase or decrease property value has not been determined, though the Southern Flow Corridor restoration resulted in a near term, net increase in surrounding property values (National Oceanic and Atmospheric Administration (NOAA), 2021). Economic interest was seen as a criterion that would be less impactful to decision making than the higher prioritized criteria.

The need to decide or implement changes within a certain timeframe varies from stakeholder to stakeholder, and managers were willing to consider time constraint needs under the urgency criterion. There were already existing expectations for when the decision should be made based on the availability of funding. There were additional temporal considerations based on the poor condition of the Burton-Fraser Road; costs to Tillamook County to repair the road could be avoided if an early decision were made to allow the TRW Restoration project to remove or modify the road.

Interest from the public is sought but will have less influence on the restoration design and plan approval decisions than other criteria. The TEP managers want to consider the expressed interests from all stakeholders, but other factors such as influence, rights, impact, and proximity were given greater weight as decision criteria.

Decision makers are likely to consider economic and property rights more heavily than fairness. The TEP restoration managers want to make sure that stakeholders do not feel left out of the process but consider that other criteria are more persuasive in the decision-making process.

Using EPA's environmental justice screening and mapping tool EJSCREEN (United States Environmental Protection Agency (U.S. EPA), 2023) and a 2.0-mile ring centered at the TRW Restoration site, EPA researchers determined that no significant underrepresented or underserved communities may exist in proximity to the TRW Restoration site. A 2.0-mile ring centered at the TRW Restoration site has an approximate population of 4,395 people, which includes large parts of the town of Tillamook, and has a 45% rate of low-income population, which is a higher rate as compared to state and national averages (29% in Oregon, 30% average in the USA). All other EJSCREEN indicators for environment, demographics, and environmental justice within this radius were comparable to or below state and national averages. Thus, consideration of the concerns for underrepresented and underserved populations was given a low weight. If this assessment is incorrect, this criterion could be given greater weight and the analysis repeated. However, there may be other more nuanced reasons to determine whether communities impacted by the restoration project are environmental justice communities that cannot be captured due to EJSCREEN's limitations.

3.2 Stakeholder prioritization

The results of the stakeholder prioritization can help show how stakeholders might be unexpectedly similar or disparate in how they fulfill any of the decision criteria, and how differing scores or emphasis placed by setting the decision context will affect the outcome of stakeholder prioritization. The Tillamook Shooters Association and County Agencies stakeholder might seem like disparate groups in how they fit the decision criteria, yet the two have similar scores across most decision criteria, except urgency, proximity, rights, and underrepresented and underserved populations. The TEP and partners, and NCLC Landowners are two stakeholder groups that have similar characteristics regarding the decision criteria, but they differ in proximity and rights. All stakeholder groups fulfilled, to some degree, the influence, interest, urgency, proximity, rights, and fairness criteria. All groups have scores of 100 for fairness, which was set because the restoration managers felt that every stakeholders' interests need to be considered and might feel that each would say their interests need to be considered fairly in the decision-making process. State Agencies, Federal Agencies, and the Dairy Community stakeholders did not score for impact, and Utilities, Commuters, and General Public did not score for economic interest (Figure 4). The tool-generated stakeholder prioritization shows that Industrial Dairy Neighbors, Funders, Commuters, State Agencies, and Federal Agencies all have similar relative priority (Figure 4), though they have different contributing resulting priority for individual criterion, such as for impact, proximity, economic interest, or rights.

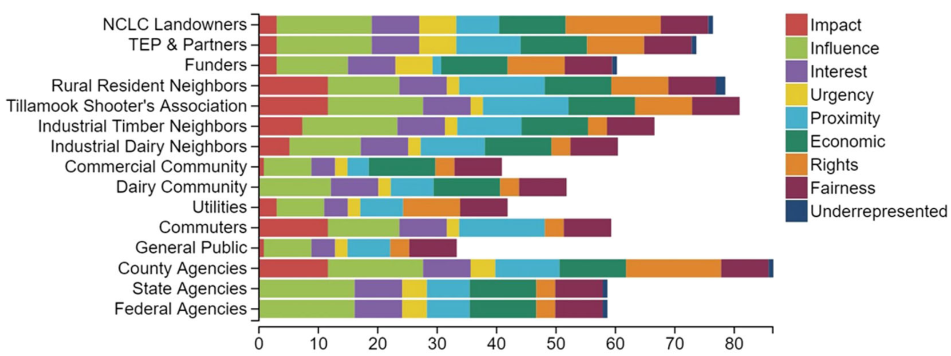

FIGURE 4
Relative priority of stakeholders based on their scores for each weighted decision criterion.

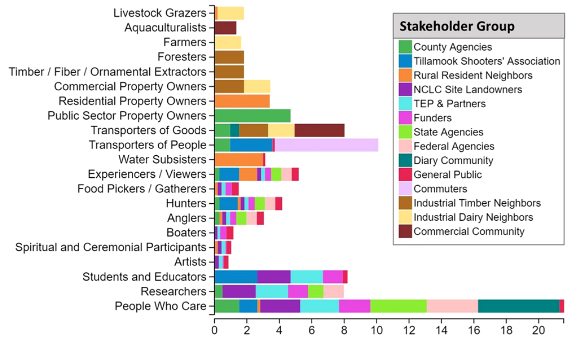

FIGURE 5
Relative priority of beneficiaries affected by Tillamook River Wetlands Restoration, determined by the beneficiary roles of each stakeholder.

3.3 Beneficiary prioritization

The results from the beneficiary prioritization step of the tool shows the suite of beneficiary groups that the TEP restoration managers expect to be represented by stakeholder groups (Figure 5). A total of 21 beneficiaries were identified amongst all stakeholder groups. Of those, 12 beneficiary groups resulted in a relative priority value of 3.0 or above (Hernandez et al., 2022). Lower-scoring beneficiaries are likely to have less influence in the final prioritization of ecosystem attributes, yet their attribute interests could align with more highly ranked and thus influential beneficiary groups. The result can help decision makers generalize which beneficiary groups may have greater or lesser interest or potential to be generally impacted in by the restoration decision.

The beneficiary prioritization results help to show where stakeholders have shared interests (Figure 5). For example, the Tillamook Shooters Association is interested in youth education pertaining to safe hunting practices on adjacent property, so their beneficiary profile includes recreational hunters who are interested in potential production of game animals that can be bolstered by restoration decisions and then migrate onto the adjacent association's property. The General Public group includes students and educators who will have access to the restored site and can use the area to learn about wetland ecology, processes, or associated species. Rural Residential Neighbors includes homeowners and renters who the TEP restoration managers felt will likely appreciate viewing local wetland plant communities. This identification of beneficiaries helps create a more comprehensive view of how different groups of people interact with the environment and creates opportunities to identify what uses or benefits are shared among stakeholders, especially when those shared interests may not be otherwise obvious (Sharpe et al., 2020).

The top beneficiary is People Who Care, a beneficiary role represented by ten stakeholder groups. However, the end points of what existence values people care about deserves to be more nuanced. The Dairy Community group includes people who care that ecosystems support farm production, which might be different than, or in addition to caring that tidal wetland ecosystems sustain healthy habitats for salmonid species. Many of the stakeholder groups that make up this beneficiary group were identified as caring that the TRW Restoration site be restored to tidal wetlands.

The second prioritized beneficiary role is Transporters of People. This beneficiary is highly prioritized because the Commuters stakeholder group only includes transporters of people as a beneficiary role. The Tillamook Shooters Association has 30% of its beneficiary profile for the transporters of people beneficiary. The General Public and County Agency stakeholder groups also have a role as Transporters of People.

Students and Educators were present as beneficiaries within the Tillamook Shooters Association, NCLC Landowners, TEP & Partners, Funders, and General Public stakeholder groups (Figure 5). There was interest by all these stakeholders to create opportunities for environmental education at the site and to educate the public about ecological and wildlife features at this site.

Transporters of Goods was included in the beneficiary profiles of industrial/commercial stakeholders (Commercial Community, Industrial Timber, Industrial Dairy Neighbors, and greater Dairy Community; Figure 5), who use the stretch of Burton-Fraser Road adjacent to the site for transporting their goods. This is especially true for commercial stakeholders located close to the TRW Restoration site.

The NCLC landowner, TEP & Partners, Funders, State Agencies, and Federal Agencies included Researchers in their beneficiary profiles (Figure 5). All these stakeholders are interested in conducting or supporting environmental research at (or including) the TRW Restoration site. This includes research on tidal wetland restoration.

The Experiencers/Viewers beneficiary was included in the profiles of nine stakeholder groups (County, State and Federal Agencies, Funders, NCLC, TEP & Partners, Tillamook Shooters Association, Rural Resident Neighbors, and General Public). While a less tangible benefit, and often a very subjective one, a popular recreational draw in Tillamook Bay and the Oregon coast is the composite features of nature that are regarded as aesthetically pleasing. Oregon Department of Fish and Wildlife Marine Resources Program's human dimensions research has surveyed visitors to the Oregon coast and found that going to the beach, sightseeing and wildlife viewing were the top two main activities and purposes for visiting the coast (Fox et al., 2022). Opportunities and access for outdoor experiences and views may serve alongside a diverse set of other activities that these stakeholder groups are interested in benefitting from and sustaining.

Public Sector Property Owners were only associated with County Agencies, but it comprised 75% of that influential stakeholder's beneficiary profile. The county owns Burton-Fraser Road which floods frequently and is in need of repair. Modification or removal of the road were major considerations in the TRW Restoration design decisions.

Hunters were included in the beneficiary profiles of nine stakeholder groups (County, State, and Federal Agencies; Funders, General Public, NCLC Landowners, Rural Resident Neighbors, TEP & Partners, and Tillamook Shooters Association). State and federal agencies regulate hunting and have interest in maintaining recreational benefits and resources for hunters. The County Sherriff is interested in maintaining hunter safety. The TEP & Partners and NCLC have interest in creating and managing habitats for wildlife used by recreational hunters.

Industrial Dairy and Industrial Timber Neighbors include Commercial Property Owners as beneficiaries. These agricultural businesses rely on properties that are upland of the restoration site. Residential Property Owners was a benefit only associated with Rural Resident Neighbors, but it comprised 40% of that stakeholder's beneficiary roles. While few residents comprise this group, they may have an outsized influence on the restoration plan which could potentially impact property values.

The General Public and Rural Resident Neighbors were the only stakeholder groups that included Water Subsisters as beneficiaries. As much as 96% of the score for this beneficiary was contributed by Rural Resident Neighbors.

Anglers were included in the beneficiary profiles of eight stakeholder groups (County Agencies, Rural Resident Neighbors, NCLC landowners, TEP & Partners, Funders, General Public, State, and Federal Agencies). State agencies permit and regulate fishing. All groups have interest in maintaining recreational benefits and resources for anglers, and the habitats of the species targeted by recreational anglers.

3.4 Environmental attributes

The FEGS Scoping Tool results of environmental attributes shows which attributes of nature are important to each beneficiary group based on the NESCS Plus broader categorization of beneficiaries (e.g., Transportation includes the Transporters of Goods and Transporters of People beneficiaries; Newcomer-Johnson et al., 2020). There were 43 environmental attributes identified as part of at least one beneficiary's profile (Figure 6).

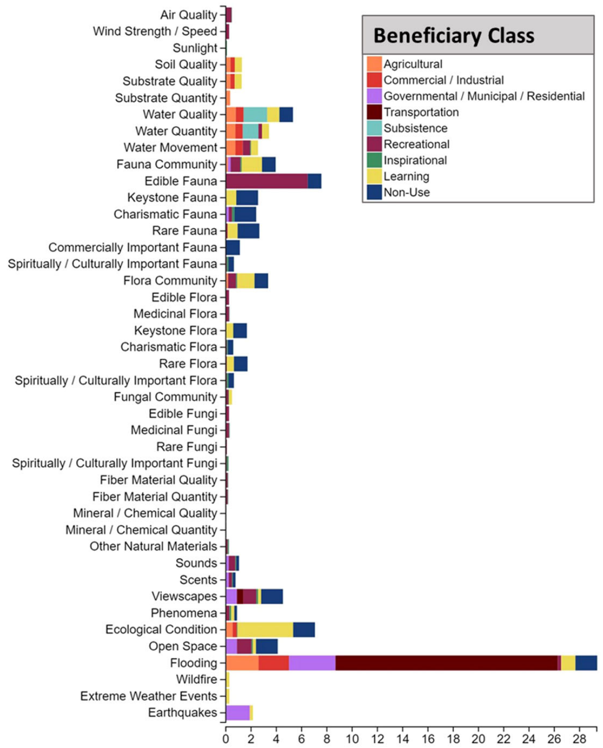

FIGURE 6
Relative prioritization of environmental attributes results from building a profile of suite of attributes that each beneficiary group cares about or needs. Beneficiary groups belonging to the same NESCS plus beneficiary class (e.g., Livestock Grazers, Aquaculturalists, Farmers, and Foresters collectively belong to the Agricultural beneficiary class) are grouped together in the legend.

Individuals may care about multiple aspects of the environment at a site but when acting as a specific beneficiary, there is a subset of biophysical attributes that provides the benefits that are necessary to provide the direct interests in using, consuming, or appreciating nature (i.e., valued environmental attributes). The number of environmental attributes valued varied among beneficiaries. Each beneficiary had 100 points to distribute across all attributes of interest or concern. Some beneficiary groups, such as Hunters, primarily valued edible fauna (and thus give this attribute a high score), while Students and Educators valued multiple subcategories of environmental attributes for the purpose of studying various components while visiting the site, meaning that there might be many attributes with relatively smaller results due to wider dispersed interests contributed by Students and Educators.

Highly prioritized environmental attributes may become more focal in driving decision making, setting goals for outcomes and monitoring. The top environmental attribute was flooding, which was valued by seven beneficiary groups and received the greatest contribution by Transporters of Goods and People, but it was also important to six additional broader categories of beneficiaries. This attribute reflects the composite natural features that mitigate flooding at the site, which was one of the driving concerns and impetus for the restoration easement. Edible fauna was the second most highly ranked environmental attribute, valued by Hunters, Anglers, and People Who Care. Edible fauna, like flooding, was highly prioritized in part because Hunters and Anglers have over 90% of their collective scoring going to edible fauna.

Ecological condition was a composite attribute that includes the overall ecosystem(s) and the associated physical, chemical, and biological processes, communities, and characteristics. It was one of the top attributes because most beneficiaries included this attribute in their profile. In discussions between the researchers and TEP restoration managers, we decided to include various composite interests related to ecological condition, but only those associated with other endpoints such as the holistic environmental conditions needed for supporting farming, artistic and inspirational uses, outdoor learning, and research events.

Water quality was an attribute important to agricultural beneficiaries, which include Aquaculturalists, Farmers, and Livestock Grazers who mainly use adjacent land parcels. About half of the overall results for this attribute also came from Non-Use (People Who Care) and Subsistence beneficiaries. Different aspects of water quality conditions include endpoints for farming, downstream oyster farms, and private well water use, in addition to the importance some might place to simply know that the water quality meets certain desirable criteria. Other beneficiaries who place an importance on water quality included Learning beneficiaries (Researchers, Students and Educators) who may use the site to study or learn about water properties and related biophysical processes. It may be important to note that specific properties and parameter thresholds to characterize water quality may be different for different beneficiaries and stakeholders.

Viewscapes was an important attribute to Non-Use beneficiaries (People Who Care), and Recreational (Experiencers and Viewers), Inspirational (Artists, and Spiritual and Ceremonial Participants) and Residential beneficiaries. Residents may be motivated to live in the area for the view from their properties, Transporters of People as drive-by-sightseers, and Students and Educators for both the view and accessibility of the site as an outdoor classroom. Seven total beneficiary subclasses cared for this composite attribute.

Open space was a composite important attribute to various beneficiaries in Learning, Inspirational, Recreational, Non-Use, and Government/Municipal/Residential classes. The NESCS Plus refers to open space as an opportunity for urban development (Newcomer-Johnson et al., 2020), but because the TRW Restoration site was designated for conservation, we used this attribute to refer to the long-term existence of undeveloped, green open space.

Fauna community was an important attribute to seven beneficiaries: Aquaculturalists, Residential Property Owners, Experiencers/Viewers, Artists, Students and Educators, Researchers, and People Who Care. For this attribute, the specific benefits for an individual beneficiary group were expected to vary. The fauna community that benefits Aquaculturalists may be different than the fauna community that draws in artists or researchers.

Water quantity was important to Water Subsisters, Researchers, Livestock Grazers, Aquaculturalists, Farmers, Experiencers/Viewers, Boaters, and Commercial Property Owners. The largest portion of the results was contributed by Water Subsisters, who are made up of the neighbors that depend on private well systems. The specific benefits of this attribute included home use, water for livestock and forestry, and small craft navigation.

Flora community was valued by Aquaculturalists, Artists, Experiencers/Viewers, Food Pickers/Gatherers, People Who Care, Students and Educators, and Researchers. The specific benefits of this attribute for an individual beneficiary also may vary, as the flora composition that benefits Aquaculturalists may be different than what attracts Artists or for People Who Care that a diverse, native vegetation community exists at the site.

3.5 Beneficiaries x environmental attributes

The TEP restoration managers were interested in exploring how beneficiary subclasses contribute to environmental attribute results, and how environmental attributes are distributed among stakeholder groups. The tool uses an MCDA approach to rank the alternatives on the sum of weighted criteria (Sharpe et al., 2020). We used the data from the weights and scores to analyze the relative priority of environmental attributes for each beneficiary subclass (Table 3), and the environmental attributes for each stakeholder groups (see section below; Table 4).

The tool produces the environmental attribute prioritization result based on the broader categorization of beneficiaries by NESCS Plus (Figure 6; Newcomer-Johnson et al., 2020). While the FEGS Scoping Tool results make the visual representation more straightforward to convey, it can be challenging to attempt to tease out how much an individual-beneficiary contributions to environmental attribute results. We used the spreadsheet calculations of the FEGS Scoping Tool data outputs to explore the attribute prioritization result at a finer scale and create a heat map to examine the distribution of attribute scores for each beneficiary group (Table 4).

The recreational class of beneficiaries has five subclasses that include Anglers, Food Pickers/Gatherers, and Hunters. The results of the heat map on Table 3 show that the edible fauna attribute is highly valued by Hunters and Anglers, but not by Food Pickers/Gatherers, suggesting that specific types of edible fauna and degree of importance can vary among beneficiary subclasses of the same class. The learning class of beneficiaries is made up of Students and Educators and Researchers, and ecological condition is significantly valued by Students and Educators for the interpretation that educational opportunities at the restoration site may focus on an overview of composite ecological condition.

3.6 Stakeholders x environmental attributes

The restoration managers were also interested in exploring how the environmental attribute results related to the stakeholder groups, which is not an output provided by the FEGS Scoping Tool. The top nine environmental attributes that had a total result score of 3.00 or higher are represented in Table 4 (see Supplementary Materials for full heat map). This analysis depicts how prioritized environmental attributes are distributed among stakeholder groups and represents a novel approach in using the FEGS Scoping Tool data to illustrate shared interests among stakeholder groups.

Flooding is a top concern for most stakeholder groups, but especially for those that are in closer proximity, such as the County Agencies, compared to State and Federal Agencies. General Public has a wide variety of beneficiary roles (Figure 3) that result in being represented by a larger interest in edible fauna over flooding. Commuters are a stakeholder that has a singular beneficiary, Transporters of People, whose main concern for the decision was flooding (Table 3), which is evident in the very high value for flooding for Commuters. Industrial Timber Neighbors have beneficiary roles that were equally distributed among Foresters, Commercial/Industrial and Transporters of Goods, all of which shared flooding as the main attribute of concern.

4 Discussion

Identifying some stakeholders was straightforward, such as the groups that spearheaded the acquisition for the land at the restoration site and who are supporting the restoration and management. Setting the decision context was important, and necessary to keep focus on who and what interests and impacts to include. Since there were different adjacent land uses that have been or pose to be impacted by flood events and by management interventions, we included those distinct groups. Utilities were one group that was considered because the TEP managers wanted to include local utility providers that likely have infrastructure running through the site, though at the time they were not sure how the stakeholder may be impacted or what beneficiaries they would represent in the restoration project. This is an example of including a potential stakeholder that may not ultimately

TABLE 3 Results of beneficiary interests for each of the top nine environmental attributes.

	Beneficiary Classes and Subclasses																					
	Agricultural				Commercial/Industrial		Municipal/Residential		Transportation		subsistence	Recreational					Inspirational		Learning		Non-use	
Environmental attributes	Livestock grazers	Aquaculturalists	Farmers	Foresters	Timber/Fiber/Ornamental extractors	Commercial property owners	Residential property owners	Public Sector Property Owners	Transporters of goods	Transporters of people	Water subsisters	Experiencers/ viewers	Food pickers/ gatherers	Hunters	Anglers	Boaters	Spiritual and ceremonial participants	Artists	Students and educators	Researchers	People who care	TOTAL
Flooding	0.34	0.15	0.31	1.88	1.88	0.65	0.92	2.93	8.38	10.03	0.00	0.05	0.00	0.00	0.00	0.24	0.00	0.00	0.60	0.58	1.81	30.75
Edible Fauna	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.91	2.85	0.00	0.00	0.00	0.00	0.00	1.13	7.89
Ecological Condition	0.19	0.17	0.17	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	4.03	0.58	1.81	7.35
Water Quality	0.34	0.15	0.31	0.00	0.00	0.65	0.00	0.00	0.00	0.00	1.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.58	1.13	5.53
Viewscapes	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.53	0.00	1.08	0.00	0.00	0.00	0.00	0.05	0.09	0.26	0.00	1.81	4.70
Open Space	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.54	0.00	0.43	0.00	0.24	0.05	0.05	0.26	0.00	1.81	4.27
Fauna Community	0.00	0.15	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.81	0.00	0.00	0.00	0.00	0.00	0.09	0.86	0.83	1.13	4.08
Water Quantity	0.32	0.15	0.29	0.00	0.00	0.61	0.00	0.00	0.00	0.00	1.30	0.05	0.00	0.00	0.00	0.24	0.00	0.00	0.00	0.58	0.00	3.55
Flora Community	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.12	0.00	0.00	0.00	0.00	0.09	0.86	0.58	1.13	3.47

The last column is the total result score for each attribute. For visual ease, individual result values are highlighted, high-to-low, with the darkest to lightest shading as follows:

Result	> 4.00	2.00 to 3.99	1.00 to 1.99	0.50 to 0.99	0.10 to 0.49	< 0.10

TABLE 4 Results of stakeholder interests for each of the top nine environmental attributes.

	Stakeholders														
Env. Attributes	County Agencies	Tillamook Shooters Association	Rural Resident Neighbors	NCLC Landowners	TEP & Partners	Industrial Timber Neighbors	Industrial Dairy Neighbors	Funders	Commuters	State Agencies	Federal Agencies	Dairy Community	Utilities	Commercial Community	General Public	Total
Flooding	4.35	2.34	0.97	0.47	0.47	5.58	2.44	0.45	6.97	0.39	0.39	1.10	0.00	4.34	0.51	30.75
Edible Fauna	0.42	0.87	0.25	0.47	0.47	0.00	0.00	0.83	0.00	1.40	1.39	0.31	0.00	0.00	1.48	7.89
Ecological Condition	0.12	1.20	0.03	1.25	1.25	0.18	0.52	0.99	0.00	0.39	0.39	0.50	0.00	0.17	0.37	7.35
Water Quality	0.08	0.17	1.78	0.34	0.34	0.32	0.94	0.28	0.00	0.27	0.28	0.31	0.00	0.15	0.26	5.53
Viewscapes	0.17	0.46	1.09	0.30	0.30	0.00	0.00	0.31	0.37	0.45	0.42	0.50	0.00	0.00	0.33	4.70
Open Space	0.13	0.34	1.01	0.31	0.31	0.00	0.00	0.37	0.00	0.45	0.42	0.50	0.00	0.00	0.42	4.27
Fauna Community	0.13	0.44	0.36	0.55	0.55	0.00	0.00	0.47	0.00	0.42	0.44	0.31	0.00	0.15	0.27	4.08
Water Quantity	0.03	0.01	1.20	0.16	0.16	0.30	0.89	0.17	0.00	0.09	0.11	0.00	0.00	0.15	0.27	3.55
Flora Community	0.10	0.39	0.11	0.49	0.49	0.00	0.00	0.44	0.00	0.34	0.35	0.31	0.00	0.15	0.28	3.47

The last column is the total result score for each attribute. For visual ease, individual result values are highlighted, high-to-low, with the darkest to lightest shading as follows:

Result	>2.00	1.0 to 1.999	0.5 to 0.999	0.1 to 0.499	<0.099

hold beneficiary roles in the decision context and is an approach relevant to other decision contexts. Furthermore, the tool preferences can be revised and re-calculated if the TEP restoration managers determine that Utilities have beneficiary roles or other interests in this case that should be accounted for in the environmental decision making. Using the FEGS Scoping Tool in an iterative nature is an approach relevant here and other decision contexts or applications.

There are environmental attributes and ecological processes that may be affected by restoration interventions, that impact less adjacent stakeholders, such as aquaculture operators and fishing industries (Commercial Community) who are downstream of the restoration site. Ultimately, we also decided to include a somewhat broad scope of stakeholders, including other actors who may potentially be able to exercise some influence or be impacted, such as the greater dairy community of Tillamook, three levels of government agencies (county, state, and federal), the public, and people who use the road that currently intersects the site, even if they do not reside in adjacent properties.

When examining each stakeholder group to characterize beneficiary roles, maintaining focus on the decision context was imperative because there are stakeholder groups with clear interests and benefits that do not pertain to the decision context at the restoration site. For example, there are commuters who may be interested in recreational benefits, making art inspired at the site, or care about the existence of a restored wetland, but we considered only what beneficiary roles are pertinent to a commuter. When identifying the beneficiary roles of a stakeholder, we considered how that stakeholder would interact with the TRW Restoration site, and not at other sites or as other roles that do not pertain to the defined stakeholder.

In characterizing what environmental attributes were of interest for each beneficiary role, we considered what aspects of the environment were important for how the beneficiary would be directly using, consuming, or appreciating nature at the restoration site. One area that was challenging to conceptually overcome during discussions was how coarse an environmental attribute could seem to the TEP restoration managers when considering how one element could represent different uses, aspects, or even interpretations of nature to different beneficiary roles. For example, edible fauna may be an attribute that signifies fish and shellfish of interest to an aquaculturist or fisherperson, but it may refer to the terrestrial community of waterfowl and mammals of interest to hunters. These nuances are difficult to parse out directly in the FEGS Scoping Tool, but they are important to keep track of in case they need to be parsed out in decision making, or perhaps in later stages of planning the restoration project, such as in setting goals, or identifying monitoring metrics and communication strategies. Thus, the TEP restoration managers were also interested in seeing how environmental attribute interests are distributed among stakeholder groups and the narrower classification of beneficiary groups. Being able to visualize those more individualized results can help to transparently interpret the nuances of environmental attributes for both stakeholder and beneficiary groups. This visualization of results can be useful for other decision contexts or applications of the tool.

There were 21 total beneficiary roles and 43 environmental attributes identified, so interpreting and taking into account how each track to a stakeholder's interest may seem challenging to incorporate into discussions and decision making. To focus on the beneficiaries and environmental attributes most prominently represented and shared by stakeholders, we set a threshold value of 3.00 or greater for a more detailed analysis (see Supplementary Materials for full results of Tables 3, 4). A value of 3.00 or more was chosen because that includes a wide range of result values, up to 30.75 for Flooding. Other attributes below a result of 3.00 may yet be important to consider (for more details, the reader is directed to Hernandez et al., 2022). Despite using an abbreviated set of environmental attributes distributed across stakeholder and beneficiary groups, the full suite could be used to communicate the results of this analysis or be used to widen the scope of considerations in the decision-making process.

This study demonstrated the transferability of the FEGS Scoping Tool and NESCS Plus as decision-informing tools to other applications. Many of the decisions made about how to utilize the tool are relevant to other decision contexts or applications of the tool. Furthermore, as this tool can be applied iteratively, as new information about interested stakeholder groups and their preferences can be updated into the tool when new knowledge is obtained. The tool itself can be used as part of a participatory exercise to more directly discover what attributes are of most common interest among stakeholders, and those attributes could be suggested to closely incorporate into decision making and throughout the process of restoration and monitoring. Since flood damage is a current reality and flood events are projected to increase damage to the road that bisects the TRW Restoration site, it was no surprise that flooding was the top attribute of concern. As such, we suggest that if TEP restoration managers, or involved stakeholders, are interested in examining how the cadre of other benefits and environmental attribute interests overlap without the obvious flooding concern, an alternative application of the FEGS Scoping Tool could be run without considering flooding to allow the results to highlight the degree of shared interests among other attributes. This alternative, iterative application of the tool could also be a way to examine how interests would differ in a situation where flooding was not a collective concern.

The FEGS Scoping Tool provided a methodical way to critically think of what boundaries to set and bend when conceptualizing what beneficiary roles a stakeholder group was interested in with regard to the restoration site and decision context, and what attributes are needed to realize the benefits of interest. This research used a novel application to explore stakeholder interests and dynamics, tying ecosystem services and the associated human well-being endpoints into a restoration context. This study also used the data inputs of the FEGS Scoping Tool to conduct an additional analysis to convey the connections between stakeholders, beneficiaries, and environmental attributes using a heat map communication approach. The use of a heat map to visually communicate results can be valuable in other decision contexts or applications of the tool. The types of results can be used to communicate risk, potential impacts, or can target communications about progress in restoration and monitoring to the specific concerns of stakeholders and their interests in the ways they directly use, enjoy, or consume aspects of the environment.

5 Conclusion

The FEGS Scoping Tool application for the TRW Restoration project was conducted through a series of virtual conversations between TEP restoration managers and EPA scientists before the tool became publicly available. Early stages of the restoration project planning make an ideal time to use the FEGS Scoping Tool to explore the social-ecological interests of people who may be affected by the project. The tool created an opportunity to use a multi-criteria decision approach to transparently identify priorities rather than allow a subset of stakeholders to dominate decisions because they are the most vocal. This approach is especially important when the stakeholder dynamics and interests require transparency and an equitable approach for community support. The analysis from the tool also elucidated overlapping interests among groups that may not have been realized by the TEP restoration managers elsewise.

In this study, the FEGS Scoping Tool was used to examine what environmental attributes to prioritize in the TRW Restoration site considering restoration scenarios that either upgrade or replace the currently existing road. A limitation of this approach is that results reflect the inputs according to the knowledge of TEP restoration managers at that point in time, thus a risk of result bias toward the assumptions of stakeholders' interests from the viewpoint of TEP restoration managers. The results are intended to inform restoration planning discussions with stakeholders, so inaccuracies may become revealed in the course of those discussions. The data inputs for this application of the FEGS Scoping Tool can then be revised to reflect the updated understanding of stakeholders' common ecological interests. Further, the tool could be used in a participatory, iterative fashion with direct input from stakeholders to allow them to make sure their groups and perspectives are most accurately represented.

The results of the FEGS Scoping Tool and heat map analyses can be used to identify what benefits and concerns are of greatest interest to stakeholders and is transferable to other decision contexts and scenarios. This can inform the process of identifying social-ecological goals for the project. The novel application of heat maps in this study can be especially useful in identifying the nuances of environmental attributes of interest to specific stakeholders, which may be useful in developing communication strategies with non-expert audiences. Overall, this can help build trust with the public and community leaders.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

CH: Conceptualization, Formal Analysis, Validation, Writing – original draft, Writing – review & editing, Data curation, Investigation, Methodology, Project administration. LS: Conceptualization, Formal Analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. CJ: Formal Analysis, Investigation, Methodology, Project administration, Validation, Writing – review & editing. MH: Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing. TD: Investigation, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2024.1290090/full#supplementary-material

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Human well-being and natural infrastructure: assessing opportunities for equitable project planning and implementation

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There is consensus within psychological, physiological, medical, and social science disciplines that active and passive exposure to nature enhances human well-being. Natural infrastructure (NI) includes elements of nature that can deliver these ancillary well-being benefits while serving their infrastructure-related purposes and, as such, offer great promise for agencies including the U.S. Army Corps of Engineers as a means of enhancing economic, environmental, and societal benefits in civil works projects. Yet, to date, NI are typically framed as alternatives to conventional infrastructure but are rarely competitive for project selection because there is no standardized approach to demonstrate their value or justify their cost. The infrastructure projects subsequently selected may not maximize societal well-being or distribute benefits equitably. A framework is needed to capture diverse and holistic benefits of NI. As part of ongoing research, this paper describes the components necessary to construct a framework for well-being benefits accounting and equitable distribution of NI projects and explores how they might be applied within a framework. We conclude with methodological examples of well-being accounting tools for NI that are based on ongoing research and development associated with this project. The findings provide insights and support for both the Engineering with Nature community and the community of NI practitioners at large.

KEYWORDS

well-being, nature-based solutions, equity, benefits accounting, nature-deprived communities, environmental justice

1 Introduction

Natural Infrastructure (NI) refers to an area or system that is naturally occurring, naturalized (i.e., converted from grey infrastructure to natural), or constructed to mimic naturally occurring, ecological or geological features and then intentionally managed to enhance ecosystem value and provide social and economic benefits (DiFrancesco et al., 2015; Roy, 2018). An expanding body of research highlighting the diversity of benefits that can be achieved by NI—such as building coastal resilience (Bridges et al., 2015), mitigating and adapting to climate change (Griscom et al., 2017; Choi et al., 2021), and enhancing biodiversity conservation (Key et al., 2022; McKay et al., 2023; van Rees et al., 2023a, 2023b)—has prompted greater demand for their use to meet traditional engineering objectives (e.g., mitigate flood risk). As such, efforts are underway to facilitate the use of NI because an array of advancements is needed to overcome challenges that accompany implementing as-of-yet unconventional projects. The need for such advancements is confirmed in the U.S. Executive Office of the White House "Roadmap", which calls for federal agencies in the US to update policies and conduct research to fill knowledge gaps and build the evidence base (White House Council on Environmental Quality et al., 2022).

Research and development are progressing to both improve the evidence base for NI and translate that evidence into accounting methods that practitioners can employ in project alternative analysis. Enumeration of benefits is an important task in new project justification, both for formal economic analysis as well as for stakeholder buy-in, and for which a need for greater comprehensiveness has been expressed (e.g., James, 2020, 2021). In essence, planners must build a business case to establish that projects are justified by the public benefit they will yield. This aligns with the economic welfare theory objective of allocating resources in a manner that maximizes the net effect on human well-being (Hicks, 1939). Failure to more completely assess the scope of social and environmental benefits that prospective NI projects may offer leads to undervaluation and an inability to truly compare NI with traditional engineering alternatives. Although US federal policy is evolving to support comprehensive benefits accounting by requiring Federal investments in water resources to evaluate environmental, economic, and social benefits[1], the existing toolbox at the disposal of planners for including the diverse benefits of NI is not yet robust.

NI projects require new and expanded procedures to support benefits accounting because benefits are difficult to quantify or define, particularly as non-overlapping, and can be difficult to aggregate and compare across projects. The diversity of NI benefits to humans, along with the biophysical complexity of nature, necessitates a very multidisciplinary effort to support accounting. Benefits can include water quality improvement, mitigation of floods and droughts, food provision, employment, recreation, educational and cultural values, and many more (Hartig et al., 2014; Sandifer et al., 2015). Tools that bring these benefits into a single framework are important, as is the primary research that underpins our understanding of benefits and subsequent efforts of translate research into information that can be used in analysis (Sharpe et al., 2023). Building on the broad portfolio of work by the U.S. Army Engineer Research and Development Center's Engineering With Nature (EWN) program, the research presented here seeks to expand the range of benefits attributed to NI projects and the ability of agencies to account for them in planning. Specifically, this research focuses on the human well-being benefits of nature and how NI planning and evaluation can include these benefits.

Many of the so-called "co-benefits" of NI (i.e., positive impacts of these features beyond the primary purpose of their use in infrastructure planning) stem from the inclusion of green space and natural elements (Raymond et al., 2017) or existence at the interface of built and natural environments thereby enhancing access to beneficial spaces. Exposure and proximity to nature, urban green space, and, increasingly, blue space are widely recognized to have positive impacts on human well-being and have been proposed as public health measures (Hartig et al., 2014; Nejade et al., 2022; Hunter et al., 2023). Well-being has promise as a category of NI co-benefits because it has been recognized as useful for providing information to policy makers designing policies and regulations to enhance people's lives (Frijters and Krekel, 2021). A report by the United States Congress in the 1970s expressed concern that social well-being has not been given enough attention in federal project analysis (Ehrenwerth et al., 2022), to which a remedy is only now beginning to be developed. As such, the foundation and institutional memory to account for well-being in infrastructure planning is generally lacking.

According to the U.S. Centers for Disease Control and Prevention (CDC), well-being "can be described as judging life positively and feeling good" and includes "the presence of positive emotions and moods, the absence of negative emotions, satisfaction with life, and fulfillment and positive functioning" (Center for Disease Control, 2018), a definition they base on the foundational work on the concept by Diener (e.g., Diener, 1984) and others. Many efforts to define the connections between nature and multi-dimensional well-being exist (as in Figure 1)—for instance, the Millenium Ecosystem Assessment connects the functions of ecosystems to determinants and constituents of well-being (Millennium Ecosystem Assessment, 2005). Well-being dimensions often include health, social cohesion, safety and security, living standards, spiritual and cultural fulfilment, and others (Smith et al., 2013). Researchers have described the pathways through which nature can affect well-being; a 2016 multi-disciplinary workshop "Exploring Potential Pathways Linking Greenness and Green Spaces to Health" developed three paths: reducing harm (e.g., mitigating pollution), building capabilities (e.g., stress recovery), and build capabilities (e.g., facilitating social cohesion) (Markevych et al., 2017). Increasing attention on well-being is related to the recognition that well-being is not only a function of the absence of pathogenic influences, but

1 Principles and Requirements for Federal Investments in Water Resources. Retrieved from: https://obamawhitehouse.archives.gov/sites/default/files/final_principles_and_requirements_march_2013.pdf.

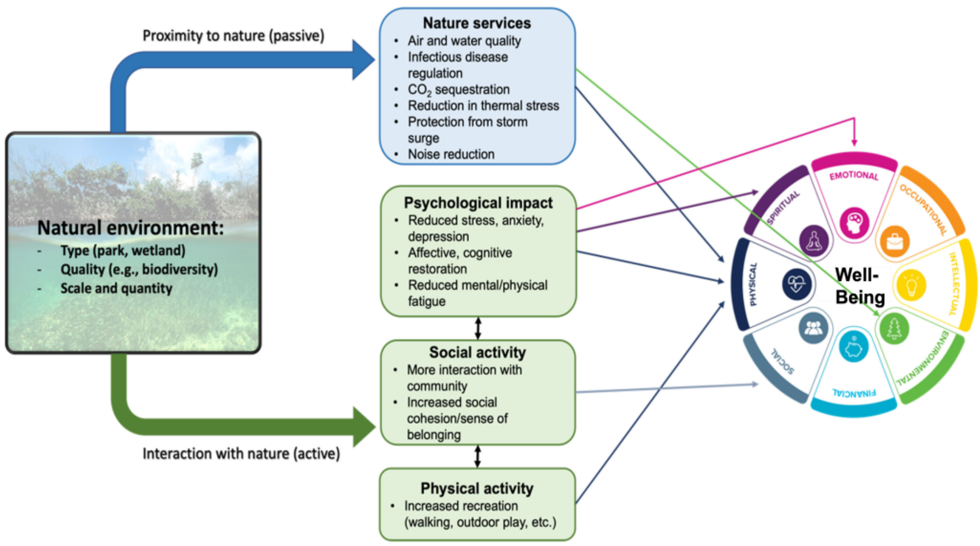

FIGURE 1
Diagram of the nature-well-being relationship (adapted from Hartig et al., 2014).

also the presence of salutogenic ones (Huppert, 2009), which is also captured by "social determinants of health" (Office of Disease Prevention and Health Promotion, n.d.). Given the potential for NI projects to have well-being benefits via these pathways, they should not be overlooked despite the challenge posed by accounting.

Beyond understanding the well-being benefits that are produced by NI projects, efforts to account for them should consider the distributional benefits. Certain communities enjoy a disproportionate share of nature-based amenities, while other communities suffer from a nature deficit (Strife and Downey, 2009; Leong et al., 2018; Flint et al., 2022; Langhans et al., 2023). This gap is recognized in the 2022 Memorandum of Understanding on Promoting Equitable Access to Nature in Nature-Deprived Communities[2], which defines nature-deprived as disadvantaged communities that disproportionately lack access to the climate mitigation and human health benefits of natural areas. Affluent, majority-White jurisdictions have been shown to benefit from higher quality park systems (in terms of acreage, access, facilities and investment) than communities with larger concentrations of low-income, ethnic minority people (Rigolon et al., 2018). Discrepancies in greenspace exposure have similarly been identified at the global scale, with Global North countries experiencing higher levels of exposure than those countries belonging to the Global South (Chen et al., 2022). Inequities in nature access and its benefits have been perpetuated by an array of sociopolitical factors. For example, historic processes of injustice have produced present-day disparities among different demographic groups (Keeler et al., 2020) including discriminatory practices embedded in zoning regulations. Although these inequities in NI benefits are generally recognized, no accounting framework currently exists for incorporating this equity gap within planning processes.

The research reported here advances well-being accounting for NI, rising to the demand for multiple intertwined outcomes: for information and tools to support practitioners in justifying investment in NI, a refocus of public investment on projects to promote well-being, and improvement in equity and environmental justice. To do so, we first compile well-being benefits accounting research—how nature and well-being can be measured and how utility functions can be used to monetize or otherwise quantify the well-being benefits of nature. We then outline a framework for NI well-being benefits accounting informed by the compiled nature-well-being relationships.

2 Framework components: the state of the research

To support the development of a framework to help agencies in meeting federal mandates for comprehensive benefits accounting, institutionalizing equity principles, and enhancing nature access amongst nature-deprived communities, existing research was first compiled. The review was guided by the desired public outcomes described above, each of which informs a component of the framework. The following sections summarize the state of the research for each of the components:

- How to operationalize nature access and exposure in order to measure nature abundance or deprivation;

2 United States Government Interagency Memorandum of Understanding on Promoting Equitable Access to Nature in Nature-Deprived Communities. Retrieved from: https://www.whitehouse.gov/wp-content/uploads/2022/09/Nature-Deprived-Communities-MOU.pdf.

- Existing human well-being indicators;
- Utility functions.

2.1 Operationalizing nature access and exposure

To support efforts to enhance nature access and, more broadly, better account for the social benefits of public infrastructure projects in planning, decision makers must identify the communities to whom well-being benefits are expected to accrue, assess their baseline access and proximity to nature, and quantify relationships between level of benefits and nature exposure/access. Understanding people's baseline access to nature is important for resolving issues of nature-deprivation and distributional equity, which is described as one dimension of equity along with recognitional and procedural dimensions by McDermott et al. (2013). Efforts to improve access to nature point to existing distributional equity, where lack of access to nature is extended to lacking enjoyment of its benefits. In general, this is supported by determining what landcover or land use constitutes nature (or the targeted nature-like space) and who benefits from it.

There is a lack of consensus or uniformity in the literature on the definition of nature, and terms such as "greenspace" or "naturalized area" are often used interchangeably to suggest the same thing. Taylor and Hochuli (2017) found papers that define greenspaces as vegetated areas, urban green spaces such as parks and gardens, recreational areas, undeveloped land, among others and that there is not clarity on whether greenspace is nature. Vilcins et al. (2022) reviewed common indicators of greenspace. They include satellite-imagery-based landcover, e.g., the normalized difference vegetation index (NDVI), fractional cover of vegetated areas, publicly accessible open space based on land use, tree counts, tree canopy cover, biodiversity indicators, and finer resolution methods such as direct observational surveys of land use and quality. Recent research encourages use of multiple measures of greenspace to capture nuance that has been observed in linkages between greenspace and health (Mears et al., 2020).

Access to nature and its benefits is generally defined in terms of geographic proximity. For instance, the Trust for Public Land's ParkServe initiative estimates that 100 million Americans, many of which are low-income, lack access to parks within walkable distances (i.e., 10 minutes or less) (Trust for Public Land, 2024). They assess this by measuring the half-mile walking distance to the closest public access point of a given park polygon and then calculating summary statistics of demographic variables within park access area boundaries. The Climate and Economic Justice Screening Tool provides geospatial data of the burdens that communities experience and identifies those that meet the criteria of being disadvantaged (White House Council on Environmental Quality, 2022). It includes lack of green spaces as a burden, defined as the amount of land in a census tract that is covered by impervious surfaces and crop land as a measure of nature deficit. Jarvis et al. (2020) use different definitions for the area of influence of nature-based solutions to account for benefits of exposure and access. Exposure was defined as the proportion of nature in a specific area around a point (used 100, 250, 500, and 1000m) and access was based on the World Health Organization (2016) recommendation that people should have greenspace should be within 300–500m of their residence. Accessibility measures often set a minimum size space (Van Den Bosch et al., 2016). Proximity is often used as a proxy for accessibility, although it is known to be imperfect because it does not account for a myriad of challenges that can exist to accessing nearby nature (Wolch et al., 2014).

2.2 Human well-being indices

Measuring trends and patterns in human well-being is a way of gauging societal progress and quality of life. Indices comprise variables assumed to influence well-being, such that improvement in a variable (e.g., air quality) should improve overall well-being scores. Index-based approaches can be advantageous because they afford researchers the flexibility to identify the aspects of a concept that are important to their specific contexts and the values of end users. For instance, a planner in Hawai'i who must allocate coastal protection infrastructure to communities within their jurisdiction based on community vulnerability may use indicators of vulnerability in his/her prioritization scheme that differ from those conceived by a planner in Florida who wishes to do the same. Further, human well-being indices provide planners with variables that they can track over time and target with policies and programs to improve well-being. Human well-being index development can support environmental management: extant indices inform sustainable development (e.g., Summers et al., 2017), conservation (e.g., Mascia et al., 2010), ecosystem recovery (e.g., Biedenweg et al., 2014; Dillard et al., 2013), and integrated ecosystem assessments (e.g., Breslow et al., 2018). Conceptualizations of well-being are diverse (Linton et al., 2016) and how it is defined will determine what is measured and whose needs are served.

Indices often disaggregate well-being into domains—understood here as the defining, theoretical components of a construct—their associated indicators—which specify measurable aspects of domains—and metrics—the concrete measurements of the construct—to organize the multi-faceted concept. For example, King et al. (2014) describe the evolution of well-being indices from a more narrow focus on economic conditions to more multi-dimensional conceptualizations that account for "material and social attributes of people's life circumstances" (p. 683) as well as psychological components. Domains comprised within various indices included: education; health; leisure time; life satisfaction and happiness; living standards; safety and security; social cohesion; and spiritual and cultural fulfillment (Smith et al., 2013). Leisher et al. (2013) found that indices most frequently employ living standards indicators followed by health indicators.

Measures of well-being range from subjective or qualitative questionnaires that gauge individuals' satisfaction (Kahneman and Deaton, 2010), to objective and quantitative, multidimensional indices that compile observable data (such as income) and calculate composite scores (e.g., Summers et al., 2014). Often, these include socioeconomic and demographic metrics found in the U.S. Census, health metrics such as levels of obesity and asthma offered by the CDC, and metrics of environmental quality such as surrounding levels of air pollution, proximity to parks, or levels of greenness. Some indices, such as the Environmental Protection Agency's Human Well-Being Index, incorporate indicators for more abstract dimensions of well-being, such as social cohesion, biophilia, cultural fulfillment, data that must often come from survey-based questionnaires (Summers et al., 2017). Despite improvements in the measurement of intangible concepts like well-being, contemporary, narrowly focused cost-benefit analysis frameworks fail to promote projects that maximize an array of socially-desirable impacts (Wegner and Pascual, 2011). The benefits associated with a natural space can arise from the activities they facilitate but also the spatial patterns of people and environment. The development of human well-being indices is constrained by data at is available to fulfill the desired variables, at the scale of the inquiry.

2.3 Utility functions

To operationalize well-being-nature relationships in a way that supports decision-making, planners must understand how incremental changes in the design of an NI project alternative will yield changes to well-being in the surrounding community. This necessitates the use of utility functions. Utility functions, used by economists to measure the value that an individual or group places on unit goods and services, are usually constructed with an assumed set of canonical properties. The principal of diminishing marginal utility is prominent among these properties. It states that the utility, or satisfaction an individual receives from the consumption of a good or service decreases with increasing consumption of that good or service. This generally implies that, all else being equal, an additional unit of income is less meaningful as the wealth of an individual increases (Kahneman and Deaton, 2010).

This concept is central to welfare economics and has been applied to public projects and policy evaluations through equity-weighted cost benefit analysis (Johansson-Stenman, 2005; Pearce et al., 2006), which weight the net benefits generated by a project according to the marginal utility of the recipients (Adler, 2016). For a variety of reasons, utility cannot be measured directly and within the context of public policy equity-based weights are at least partly normative, requiring both methodological choices and judgement (Hanley, 1992; Kind et al., 2017). This enables prioritizing benefits received by lower income individuals, since marginal utility is a decreasing function with respect to income, which in many cases is desirable (Fankhauser et al., 1997; Johansson-Stenman, 2005; Stroud et al., 2022). Nature is increasingly understood to be an inequitably provided resource that provides many non-market goods and services with concave marginal utility functions (Kruize et al., 2007; Atkinson and Mourato, 2008). Therefore, equity-weighted, utility-based cost benefit methods are expected to yield benefits when applied to policies and projects that influence access to nature and/or NI. Similarly, benefits of exposure to and accessibility of nature likely do not increase linearly, with increases in nature-deficient communities having a greater impact than nature-abundant.

3 A framework for natural infrastructure well-being benefits accounting

This research seeks to provide planning and research communities an accounting framework to estimate well-being impacts of proposed NI-based projects. The components we showcased in Section 2 can be leveraged to evaluate nature-derived benefits for well-being. We describe this framework while acknowledging that this project is ongoing and project specifics (e.g., data used, results, and so on) are still yet to be determined. The proposed framework envisions the use of an index-based approach to measure well-being as it relates to nature (later called the Nature-Centric Well Being Index) and subsequently evaluate the nature-based well-being gains using a utility function concept. As discussed above, the use of indices for attributing value to social phenomena like well-being or vulnerability is commonplace within the body of work to which this study belongs.

3.1 Development of a nature-centric well-being index

3.1.1 Scoping and design

The initial formulation of this study's scope of work and the later development of the roadmap commenced through an iterative process of setting forth core research questions, reviewing the academic literature, assessing data availability to address research questions, and, in cases where data availability was not sufficient to investigate a particular inquiry, revising and reformulating aspects of the project scope. This research is guided by one central research question and two related sub-questions, as follows:

Research Question: How can social factors, such as human well-being and health, be used alongside traditional planning tools (e.g., benefit–cost analysis) to evaluate NI projects with the goal of promoting equitable distribution of nature benefits?

(a) What are robust indicators of well-being that can be used to assess social dimensions of NI?

(b) To what extent are indicators of well-being related to indicators of nature?

It is important to note the targeted decision that this research aims to support. Whereas many research efforts use similar methods to identify geographic areas to prioritize for the addition of nature or conservation/restoration of natural areas, the research here is intended to account for the well-being impacts of nature as a co-benefit of projects with other primary purposes. Projects that incorporate nature and NI, such as living shorelines used for flood risk management and thin-layer placement of dredged material, are generally constrained to areas where they can be implemented.

Therefore, the open-ended question of where to increase nature access and proximity for people is different. Methods are needed to compare how much co-benefit can be achieved by alternative project formulations, including based on their location as well as by their form (e.g., NI versus conventional infrastructure).

3.1.2 Identifying human well-being benefits from nature as prospective indicators

Prospective indicators can be derived from the well-being benefits of nature that have been reported in the literature. These indicators are similar to those described in the ecosystem goods and services literature, as benefit-relevant indicators or indicators that measure the outcomes of ecosystem functions that are relevant to human welfare (Olander et al., 2018). Conditions of nature that impact well-being should form the basis of a nature-centric well-being index, so that a change in nature access or proximity can be expected to change well-being. Research results about the impact of nature on aspects of well-being help to strengthen the evidence that a causal relationship exists between the condition of nature and well-being, thus they have been explored in this work to inform the selection of indicators for a well-being index.

As noted previously, many researchers have defined the pathways through which humans derive well-being benefits from nature. Active benefits result from direct human interaction with a natural setting (e.g., sitting in a park or hiking on a nature trail), whereas passive benefits refer to the biological or physical functions of natural features that serve the well-being of communities in proximity to them (e.g., trees enhancing air quality or a living shoreline providing coastal protection). Both categories of benefits have been studied in a variety of natural environments and through myriad methodological approaches.

3.1.2.1 Active benefits

Research on the active well-being benefits of nature (Table 1) comes from the fields of psychology, physiology, social science, environmental justice, epidemiology, and more. The psychological benefits of nature access have received the most academic attention, with research dating back to the late 20th Century (Keniger et al., 2013; Hartig et al., 2014; Sandifer et al., 2015; Bratman et al., 2019). Such benefits include enhanced attention restoration, reduced mental fatigue, and improved academic performance, education, learning opportunities, mood, and emotional regulation. Psychological benefits of nature are often accompanied by physiological impacts. For instance, those who experience increases in positive mood states and stress reduction may also experience improvements in various health measures, such as blood pressure reduction. Table 1 summarizes benefits of active engagement with nature.

TABLE 1 Active well-being benefits of nature.

Category	Benefit	References*
Active benefits (derived from interaction with nature)		
Psychological	*Attention restoration*	Keniger et al., 2013; Kaplan, 1995; Berman et al., 2008; Hartig et al., 1991; Wells, 2000.
	Reduced mental fatigue	Kuo and Sullivan, 2001.
	Improved academic performance, education, and learning opportunities	Li & Sullivan, 2016; Wu et al., 2014; Kweon et al., 2017.
	Improved mood and emotional regulation	Keniger et al., 2013; Sandifer et al., 2015; Frumkin et al., 2017; Bratman et al., 2019; Wells and Evans, 2003; Astell-Burt et al., 2013; Kuo and Sullivan, 2001; van den Bosch and Meyer-Lindenberg, 2019; Ward Thompson et al., 2016; Catanzaro and Ekanem, 2004; Van Den Berg and Custers, 2011; Curtin, 2009; Barton and Pretty, 2010; Bowler et al., 2010; Lahart et al., 2019.
Social	*Opportunities for social cohesion*	Osmond, 1957; Peters et al., 2010; Schiefer and Van der Noll, 2017; Jennings and Bamkole, 2019; Kawachi et al., 2008; Maller, 2009; Kingsley and Townsend, 2006; Kondo et al., 2015; Francis et al., 2012; Fan et al., 2011; MacKerron and Mourato, 2013.
Physiological	*Reduced physical fatigue*	Park et al., 2011.
	Improved physical health outcomes	Douglas et al., 2017; Keniger et al., 2013; Sandifer et al., 2015; Sleurs et al., 2024
	Facilitation of active lifestyles	Hartig et al., 2014; Lahart et al., 2019.
	Enhanced immunity and reduced chronic and inflammatory diseases	Hanski et al., 2012; Rook, 2013; Lynch et al., 2014; Naik et al., 2012; Su et al., 2013; Clarke et al., 2010; Nicolaou et al., 2005; Hou et al., 2009; Beebe et al., 1967.
	Improved birth outcomes	Douglas et al., 2017; Dadvand et al., 2014; Grazuleviciene et al., 2015.

*The references listed provide evidence of each benefit. This table omits studies that do not document evidence of a given benefit.

3.1.2.2 Passive benefits

Connections between ecosystem services (i.e., the passive benefits of nature) and human health are well-established—in particular, the regulating services that mitigate natural and man-made hazards to human safety and health (Sandifer et al., 2015; Frumkin et al., 2017; Marselle et al., 2021). These benefits (summarized in Table 2) accrue to people by virtue of proximity (passively) instead of by actively spending time in natural spaces. In smaller-scale, urbanized environments, green spaces such as parks have been shown to have significant attenuative impacts on heat stress, noise, and air quality. More recent demand for nature-based flood risk management infrastructure has incited research showcasing the abilities of coastal and inland wetlands in mitigating erosion, storm surge, and heavy rainfall events. Larger-scale studies have probed the passive benefits to human health

TABLE 2 Passive well-being benefits of nature.

Category	Benefit	References*
Passive benefits (derived from proximity to nature)		
Physiological	*Lowered mortality from physiological diseases*	Mitchell and Popham, 2008; Maas et al., 2009; Wilker et al., 2014.
Protection from natural/man-made hazards	*Biodiversity and infectious disease regulation*	Blaikie and Jeanrenaud, 1996; Hough, 2014; Rudolf and Antonovics, 2005; Ezenwa et al., 2006; Mills, 2006; Ostfeld and Keesing, 2000; Wood et al., 2017.
	Air pollution reduction	Landrigan, 2017; Beckett et al., 1998; Janhäll, 2015; Namin et al., 2020; Nowak et al., 2006; Nowak and Crane, 2002; Takahashi et al., 2005; Jia et al., 2021; Leung et al., 2011; Ferrini et al., 2020; Nowak, 1994.
	Noise reduction – hearing loss	Flamme et al., 2012; Mayes, 2021; Van Renterghem et al., 2012; Van Renterghem et al., 2015; Van Renterghem and Botteldooren, 2008; Wong et al., 2010; Van Renterghem, 2019.
	Heat reduction	Environmental Protection Agency, 2008; Debbage and Shepherd, 2015; Fini et al., 2017; Sarrat et al., 2006; Rosenfeld et al., 1998; Cedeño Laurent et al., 2018; Buguet, 2007; Stone, 2012; Gillner et al., 2015; Lehmann et al., 2014; Liu et al., 2020; Ferrini et al., 2020; Brown et al., 2018; Dimoudi and Nikolopoulou, 2003; Hsieh et al., 2018.
	Flood hazard mitigation and resilience	Mason et al., 2010; Chakraborty et al., 2014; Gourevitch et al., 2022; Messager et al., 2021; Brokamp et al., 2017; Ferrini et al., 2020.
Psychological	*Noise reduction – stress*	Münzel et al., 2018; Van Renterghem et al., 2012; Van Renterghem et al., 2015; Van Renterghem and Botteldooren, 2008; Wong et al., 2010; Van Renterghem, 2019.
	Flood hazard mitigation and resilience	Brokamp et al., 2017; Chakraborty et al., 2014; Ferrini et al., 2020; Gourevitch et al., 2022; Mason et al., 2010; Messager et al., 2021; Spalding et al., 2014

*The references listed provide evidence of each benefit. This table omits studies that do not document evidence of a given benefit.

resulting from maintaining biodiverse habitats. Such studies often stem from pathological research, and in several instances, evidence points to a correlation between more biodiversity and increased disease regulation.

3.1.2.3 Takeaways from literature and caveats

Many of the studies reviewed cite the challenges of studying human well-being and attributing well-being to nature. This is because well-being is complex, being comprised of multiple domains, and nature is not a single amenity. Observed relationships between nature and well-being varied by country, gender, socioeconomic position, and, importantly, by the measure of well-being used, which vary from self-reported experiences to objective indicators like health outcomes. Furthermore, most studies demonstrate statistical relationships between the presence of nature and a well-being variable without establishing mechanisms of causality, though more recent work (e.g., Sudimac et al., 2022) is beginning to do so.

Individuals have different circumstantial requirements of nature to derive well-being benefits. Whether an individual benefits from a natural setting (or engages with it in the first place) depend on features such as accessibility (Hartig et al., 2014), perceived safety (Day, 2006; Groff and McCord, 2012; McCord and Houser, 2017; Harris et al., 2018), and the types of nature included (Fuller et al., 2007; Kweon et al., 2017; McKinney and VerBerkmoes, 2020). These research findings can be informative for the design of NI so that human well-being benefits can be explicitly sought and claimed. It is important also to note that community involvement in design, a key tenet of procedural justice and equity theories (Seigerman et al., 2022) ensures that the design reflects communities' needs (such as a sports field) and interests (such as gardening) (Nesbitt et al., 2018).

3.1.3 Selection of indicators

The development of actionable indices for well-being and ambiguous concepts alike is limited to the use of publicly available data with national coverage. Efforts to develop indicators with objective data can utilize statistical methods to aid selection and have scientific rigor (e.g., Gu et al., 2023). The general approach for selecting indicators commences with defining goals for the assessment and operationalizing these goals through a conceptual framework (Breslow et al., 2016). The process then transitions to collecting and developing candidate indicators based on data availability, defining screening criteria for selecting indicators, evaluating the candidate indicators according to these screening criteria, and selecting a suite of complementary indicators that delivers useful information toward achieving the overall goals (Breslow et al., 2016). In some instances, smaller, geographically focused efforts have used a community-driven approach for this step. For example, Biedenweg et al. (2014) solicited concerns and values of residents of a Puget Sound watershed through social science methods to develop a set of screening criteria. Once indicators are selected, the set of indicators can be evaluated empirically through statistical methods associated with external validity and internal consistency assessments, such as Cronbach's alpha, correlation analysis, cluster analysis, and classification trees (Gu et al., 2023). Following Gu et al. (2023), Cronbach's alpha analysis can be used to check the overall consistency of selected indicators and consistency within each indicator for those with multiple measures; correlation analysis allows researchers to compare relationships between each pair of measures; cluster analysis identifies expected differences between the estimations of the measured phenomenon; and, finally, a classification tree indicates the key drivers of cluster outcomes. This research follows this generalized approach in the collection of data and selection of indicators of well-being and nature described below.

3.1.3.1 Nature access and exposure indicators

As noted in the state of the research on operationalizing nature above, there are various metrics of nature abundance and access available. In this research, several nature-related datasets were gathered, including landcover data from the U.S. Geological Survey and park location data from the Trust for Public Land's ParkServe initiative, with the goal of investigating and comparing several metrics of nature. How nature (or lack thereof) is measured can be determined by, for example, grouping landcover classifications that satisfy a definition of nature, or, by contrast, grouping classifications that satisfy a definition of nature deprivation. The use of park data can serve as a complementary measure of nature access and add nuance to analyses of how well-being is impacted by the presence or lack of a natural space. To develop a nature-informed well-being index, this study proposes the use of correlation analysis to investigate statistical relationships between composite well-being scores or individual metrics with measures of nature, contingent on the assumptions of a given correlation analysis method (e.g., data are normally distributed) can be reasonably met by the available data and scope of work.

3.1.3.2 Well-being indicators

The benefits of nature on human well-being found in the literature serve to guide the selection of indicators that can be included in a nature-centric well-being index. There are significant challenges with acquiring nationwide data to serve as metrics of many of the prospective indicators, however. The research team screened multiple indices pertaining to well-being and their associated data sources based on their geographic extent (we sought nationwide data available at the census tract level, where possible) and relation to the pertinent constructs of well-being. While specific metrics have yet to be chosen, paramount among the compiled indices are the CDC PLACES dataset, which provides yearly modeled estimates of various health outcome, health risk behavior, disabilities, prevention, and health status metrics from CDC's Behavioral Risk Factor Surveillance System (see Zhang et al., 2015 for more on modeling approach). We also compiled socioeconomic and demographic data from the CDC's Social Vulnerability Index, which come from the U.S. Census Bureau's American Community Survey estimates for years 2016-2020.

3.2 Translating nature-focused well-being into benefit with utility functions

Public projects providing access to nature offer benefits to individuals and communities, including enhanced well-being and quality of life. Although these benefits are expected to have a larger impact on the well-being of individuals with lower *a priori* access, traditional evaluation methods do not capture these distributional impacts. To address this, we propose using utility functions and equity weighted cost benefit analysis to better capture these projects well-being benefits and address social equity concerns.

Utility functions are used to represent individual's preferences and well-being. These functions are usually constructed with a set of canonical properties (Moscati, 2016). The principal of diminishing marginal utility is prominent among these. It captures the idea that increased access to a good or service improves the well-being of those with limited access more than those with abundant access (Kahneman and Deaton, 2010); when applied to projects that enhance access to nature it implies that an additional unit of access to nature provides more utility to those with limited exposure, making the evaluation more sensitive to the needs of nature-deprived communities. A prototypical function with this property is the isoelastic utility function, in Equation 1.

$$u(c) = \begin{cases} \frac{c^{\{1-\eta\}}}{1-\eta} & \eta \geq 0, \eta \neq 1 \\ \ln(c) & \eta = 1 \end{cases} \quad (1)$$

Where, $u(c)$ represents the utility from consumption; c is the level of consumption, including benefits provided through access to nature; and η is the coefficient of relative risk aversion, the parameterization of which modifies the impact of inequality on risk aversion. For $\eta = 1$, the function exhibits constant relative risk aversion, meaning individuals' preference for increased nature-based benefits is invariant given their initial wealth or *a priori* access to nature. This formulation of the utility function can help isolate the degree to which increases in social welfare are driven by initial inequities, changes in access to nature, and risk aversion (Arrow, 1951; Hakansson, 1974; Kahneman and Tversky, 1979). Kind et al. (2017) analyzed the risk aversion and equity-weights used in cost benefit analysis for flood risk management projects and provides a range of plausible values for η based on previous studies. The application of utility functions further enhances the evaluation of public projects by quantifying non-market values for access to nature, which is a long standing issue in the evaluation of environmental projects (Hanley, 1992; Pearce et al., 2006). In the case of projects that enhance access to nature, we propose registering project benefits with an index derived from well-being index and measure of nature abundance or deficit. Alternative methods can use revealed preferences, contingent valuation, and proxy variables. In sum, the inclusion of utility functions enhances the evaluation of public projects by facilitating the quantification of non-market values associated with improved access to nature. It also helps to ensure that public resources are directed toward individuals and groups in society that benefit the most, through the principal of diminishing marginal utility.

A social welfare function is constructed as the sum of individuals or groups utility functions, and may be used in equity weighted cost benefit analyses (Atkinson, 1970; Duclos and Araar, 2001). Equity weighting complements the use of utility functions by addressing social preferences for more equality and, in particular, more equitable access to nature. Under this approach the social welfare function, $U(C)$ is weighted, as shown in Equation 2.

$$W = \sum \omega_i U_i \quad (2)$$

Where, U_i represents the utility or well-being of the ith individual or group; ω_i represents the weight assigned to that individual, and W is the overall social welfare or utility that incorporates equity weighting. A common weighting scheme uses income-based weights, shown in Equation 3.

$$\omega_i = \frac{1}{Y_i^{\epsilon}} \tag{3}$$

Where, Y_i is the income of the ith individual or group and ϵ is Atkinson social welfare parameter that describes aversion to inequality. For $\epsilon = 0$ there is no aversion to inequality, e.g., the income-based weights have no impact. On the other hand, larger values for ϵ increase the importance assigned to the marginal utility the lowest income individuals or groups in society. This formulation is desirable because it facilitates a sensitivity analysis, evaluating the impact of aversion to inequality of project or plan selection (Johansson-Stenman, 2005; Adler, 2016). A study by Drupp et al. (2015) provides values for ϵ acquired through expert elicitation. These values were recently applied in the analysis of a nature-based flood risk reduction project in Boston (Stroud et al., 2022). This approach addresses social and environmental justice concerns by incorporating preference for a more equitable provision of nature-based benefits, helping to ensure access to nature is provided in a manner that benefits marginalized groups and contributes toward a more inclusive and fair allocation of resources.

Formulations for a utility function will experiment with separate and combined well-being and nature indicators. Ideally, a utility function will result that can be used by project planners to evaluate the utility of a project alternative according to the context of the added nature it provides.

4 Conclusion

The fact that nature is essential for human well-being is generally known, and the inclusion of nature benefits in economic analysis of public investment, particularly in infrastructure, is relatively new and still developing. The benefits found in a limited review of existing research span many dimensions of human well-being but specific causal relationships between parameters of nature access and proximity are difficult to prove. Although research on the benefits of nature, including that presented here, is relatively utilitarian, elsewhere the value of nature conservation and restoration for more ecocentric objectives such as biodiversity is recognized. Methods to account for the inherent value of nature in project planning may also be warranted.

Research and development associated with the operationalization of intangible benefits like human well-being is paramount to influencing socially desirable decision-making surrounding the use of NI. Here, we present a roadmap for a methodology that builds on the research that has developed and applied its components: nature proximity and access, indices of human well-being, and use of utility functions to translate goods and services into quantitative benefits. In doing so, we hope to contribute to solutions that rise to the calls for both comprehensive benefit accounting for public projects and more equitable provision of nature-based benefits and fair allocation of resources. The methodology, as presented, is flexible to future advances in indicator-based definitions of nature abundance and access, as well as that of human well-being.

Importantly, the proposed methodology takes the surrounding context and community characteristics into consideration in quantification of prospective project benefits. In doing so, it can account for equity by capturing the diminishing rate of return between the level of well-being benefits and exposure to or accessibility of nature. We contend that our roadmap is well-suited to accounting for well-being benefits in NI project evaluations, particularly for government agency decision-making, and advantageous in the flexibility it offers for a variety of decision-making contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EK: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. MK: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. JK: Writing – original draft, Conceptualization. SG: Writing – review & editing, Conceptualization. EY: Writing – review & editing, Project administration, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Eco-decisional well-being networks as a tool for community decision support

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Community decision making based on the sustainability of ecosystem services is an integrated process that involves multiple complex decisions and is greatly aided by an understanding of how those decisions are interrelated. The interrelatedness of decisions can be understood and even measured based on connections between actions and services and influence of services on domains of human well-being. These connections can be formed into a network structure so that quantifiable properties of networks can be applied to understanding decision impacts. We developed an eco-decisional network based on weighted social-ecological networks as a tool for integrated decision making based on ecosystem services and human well-being. Nodes are actions, services, or domains of human well-being and they are linked by weighted influence derived from community stakeholder input. Examination of the eco-decisional network, as well as comparison to pattern in the random networks, suggest there are important patterns of influence among different influence pathways from actions to community well-being, which describe community priorities and define unique roles through which chosen sets of actions can influence human well-being. The eco-decisional network is generalized across communities but can also be made community specific, which provides a tool for comparison between communities in decisional priorities (network properties), as well as comparisons between proposed actions within a community (network paths). The well-studied properties of networks, well-established network theory, as well as established network metrics make this approach promising for application to integrated decision making and for communicating possible outcomes to stakeholders. The result is a guidance tool for connecting propose actions to ecosystem services and human well-being.

KEYWORDS

ecosystem services, human well-being, networks, community decision making, network indices

1 Introduction

Community decision making concerning natural resources and infrastructure is a complex issue that affects stakeholders through gain or loss of ecosystem services (Rutherford et al., 2018; Pouso et al., 2020). Ecosystem services are direct benefits to people from nature such as extractable resources, clean air and water, recreational opportunities, and viewscapes (Costanza et al., 1997). These services, alongside social and economic services can inform complex decisions if they can be effectively measured, and requisite decision trade-offs communicated to stakeholders (Bingham et al., 1995). The challenge lies in integration across services as most complex decisions affect multiple services at once and usually represent trade-offs as potential actions yield different integrated results. Sustainability is best understood as a whole system trait rather than through management of multiple single-issue criteria (Bodini, 2012). Many tools and strategies have been employed to identify integrated outcomes and even qualitatively rank them in terms of predicted impacts on services (Poch et al., 2004; Martin et al., 2009). However, here we are interested in quantitative options for understanding the integrated connections between proposed actions and service outcomes and argue that services-based decision making has common properties with network-based flow analysis that may be useful for understanding integrated service outcomes. Decision makers need to identify quantitative endpoints like human well-being as the outcome of all decisions made that affect all stakeholder types as a community (Costanza et al., 1997), and human wellbeing can be meaningfully used in network-based analyses of decisional outcomes.

Network tools describe connections (links) between groups of objects (nodes) that have individual identity but also form a collective whole defined by how strongly and completely the nodes are interconnected. Network tools have been used to describe social groups such as community health networks (Manning et al., 2014), energy groups such as food webs (Niquil et al., 1999), and informational/influence groups such as ecosystems (Raffaelli, 2006; Fiscus, 2009). In turn, network flows can describe connectivity but can also be used to quantify relative connection strength and even flow of materials through the network between nodes of interest to inform system robustness (Patricio et al., 2006; Jorgensen and Ulanowicz, 2009; Ulanowicz, 2009). In its simplest form, network analyses have been used to predict group organization and assembly in terms of how links are formed between nodes (Butts, 2008), but in cases where links can be weighted or quantified, network analysis allows for understanding of organization in terms of relative link strength (Zorach and Ulanowicz, 2003) and even total network throughput (Huang and Ulanowicz, 2014; Ulanowicz et al., 2014). The latter has given rise to a suite of descriptive network indices based on optimal levels of organization (Ulanowicz, 2009). Combined these network analyses have been used to explore common ground in network organization and to quantify network pathways as a method for understanding the effects of change on the network as a whole.

Here we introduce the idea of an eco-decisional network, as a derivative of social/ecological networks, in which the nodes are actions and outcomes rather than physical elements, such as in a social network connecting people. We could assemble a decisional network that linked together decision makers and stakeholders as nodes, but this would create a focus on how decisions are made, not the cause and effect of those decisions, which is our focus here. The challenge of this novel approach is to define nodes in a meaningful way and here we employ the ecosystem services concept and define nodes as either actions to be taken, services affected by these actions, or the resultant impact of change in service production on human well-being. To avoid an open-ended dichotomy, we employ a suite of action categories (Fulford et al., 2017), service categories (Fulford et al., 2015; Summers et al., 2016), and domains of human well-being (Summers et al., 2014) that have been well studied and defined based on analysis of real-world decisions. In this framework, a decision is a pathway from an action through affected services to a domain of human well-being and the network as a whole describes the decision space for a particular group of stakeholders (e.g., community) that predicts the collective impact of multiple decisions on human well-being. Our interest is in identifying the relative importance of different pathways and possibly exploiting network theory to identify useful patterns across all pathways in the network. By using an established framework for both node definition and linkages, we are tying this analysis to existing decisional science (Diener and Seligman, 2004), but also making progress in their use through the organization and analysis of network properties.

Eco-decisional networks are a hybrid concept in network analysis in that links can be weighted based on influence but flow between nodes is diverse and not conserved, so not directly comparable as in a network with a single common currency of throughput. This places a limit on the use of tools that focus on a conserved flow though the network (e.g., Ulanowicz et al., 2014). However, advances have been made in our understanding of weighted socio-ecological networks (Zorach and Ulanowicz, 2003; Dykstra et al., 2016) that provide some useful quantitative tools for constructing and analyzing decisional networks and perhaps finding some common ground for comparative study. We apply these tools to the development of the eco-decisional network and explore general and community-specific patterns in network properties as an introduction to this approach for decision support. The goal is to demonstrate tools grounded in network theory that can be used by community decision makers to support integrated decision making across multiple complex issues and be transferable to multiple communities.

2 Methods

2.1 Eco-decisional network assembly

Networks are comprised of nodes connected by links. In the case of our eco-decisional network, nodes are actions and outcomes of decisions, and links are the level of influence decisions have on services or the influence a change in services have on domains of human wellbeing. Flow influence is expressed as flow weights (sensu Zorach and Ulanowicz, 2003) and provide the basis for a network analysis of overall influence in the form of path weightings and network indices of overall information content (Ulanowicz, 2009). Again, pathways from action to well-being nodes represent potential decision options so we will explore network metrics that focus on different path choices and their relative influence on human well-being as an endpoint. First, we describe network assembly by defining node types and link weighting. This is followed by a random network analysis to look for patterns in network size and link weight distribution and for comparison to our real-world network as well as similar previous work (Zorach and Ulanowicz, 2003). We then assemble a community-specific network analysis based on community input from structured decision-making exercises in multiple index communities (described below) and place the results in the context of observed pattern as a way of generalizing eco-decisional networks across communities.

Community network elements (nodes and links) were taken from three sources and connected based on community specific data on links and weights. Human well-being (HWB) was defined using the human well-being index (Summers et al., 2014), which is based on a set of eight HWB domains (Table 1). Human well-being nodes were the outcome of planned decisions and are comprised of eight HWB domains connected to a node for the overall HWBI. Service nodes represented the initial effect of planned decisions and were defined with a set of 22 nodes defined based on analysis of connections between ecological, social, and economic services and HWB (Summers et al., 2016). These services were linked to decisions through a set of 29 action categories define based on a series of facilitated workshops conducted in nine communities across the country (Fulford et al., 2016) combined with a keyword analysis of an additional 97 community planning documents (Fulford et al., 2017). The workshops were designed to elicit information on action priorities important to each community, as well as priorities and connections among these action priorities, defined services, and the domains of human well-being.

2.2 Eco-decisional network description

Nodes in ecological and social networks are typically physical elements of the real world such as species, individuals, populations,

TABLE 1 Summary of nodes by category.

Action categories (n=29)	Service categories (n=22)	Domains of human wellbeing (n=9)
Access to natural resources	Capital Investment	Connection to nature
Preserve existence value	Production	Cultural fulfillment
Preserve sense of identity/place	Innovation	Education
Access to arts/music	Employment	Health
Access to children's programs	Re-Distribution	Leisure time
Diversity of population	Consumption	Living standards
Access to food and cuisine	Finance	Safety and security Social cohesion
Access to government (input)	Greenspace	**HWBI***
Knowledge of history	Air Quality	
Options for philanthropy	Water Quality	
Access to education	Food, Fiber and Fuel Provisioning	
Diversity of education content	Water Quantity	
Increase non-traditional options	Activism	
Access to healthcare	Emergency Preparedness	
Focus on youth education	Public works	
Access health education	Communication	
Support active lifestyle	Community and Faith-based Initiatives	
Access to basic standard of living	Education Services	
Preserve/promote local culture	Labor	
Support urban revitalization	Healthcare	
Support agriculture	Justice	
Diversity of jobs	Family Services	
Support economic development		
Healthy natural and built environment		
Access to housing/ lifestyle options		
Promote community atmosphere		
Support faith institutions		
Support population stability/retention		
Access to transportation options		

See Figure 1 for node ordering in decisional networks and Supplementary Materials for formal node descriptions as well as full link details. Items in same row are not necessarily linked in the network. The HWB nodes include eight domain nodes and one node for the overall HWBI (*).

physical locations, or objects of confluence (e.g, computer network nodes). These are useful when the network flow is left unmeasured or can be directly measured as physical transfer of energy, carbon, etc. Our decisional network measures flow as 'effect' which can come in multiple physical forms with the common outcome of altering benefits to people. The nodes in our eco-decisional network are either decision outcomes (actions), measurable benefits (services), or domains of HWB (domains). We also include a final node for an index of overall human well-being (HWBI) which is an optional upper endpoint of network flow (Table 1).

Action categories (AC; n=29) – These are nodes describing potential actions to be taken as a result of community decision making. Such actions can take many forms such as physical (e.g., build roads), financial (e.g., economic development), or legal (e.g., protect historic buildings). The Action category nodes are designed to capture a broad and comprehensive suite of potential actions which are organized into categories to maximize transferability among communities. The categories were assembled based on workshop outcomes describing action priorities combined with a keyword analyses of community planning documents. Data on specific action priorities were assembled into action category nodes based on expert opinion.

Service categories (S; n=22)– Actions yield impacts primarily as changes in services to community stakeholders. The Service category nodes describe benefit outcomes in three broad areas (environmental, social, and economic). These nodes are prescribed by well-being theory and there are 22 Service nodes used in this analysis which were described by Summers et al. (2016).

Domains of human well-being (D; n=8) – These nodes describe how service benefits to stakeholders translate to a change in human well-being. There are eight domains of human well-being as described in the HWBI overall structure and these domains create a path for a decision to affect HWBI in a measurable way (Summers et al., 2014).

Human well-being Index (HWBI; n=1) – The HWBI node is the measurable index of human well-being. This node is included as the integrated endpoint of the decisional network and allows for the domain nodes to have differing influences on overall well-being as defined by link weights.

Link weighting – Links are connections between nodes and can be defined based on measurable weight/flow, as well as directionality of flow (unidirectional/bidirectional). For instance, a social network is usually defined as unweighted and bidirectional in that connections are all equivalent and effect nodes mutually. In contrast, an ecological network may consider differences in relative flow between particular nodes and that flow may also be directional in that flow is measured from node A to node B but not from node B back to node A. The decisional network is a hybrid social/ecological network that does not measure physical flow between nodes. Alternatively, we consider differences in flow weights as the effect of a change in the source node on change in the receiver node. These weights are directional and represent the strength of influence a decision has on a service, a service has on a domain of human well-being, or the influence of individual domains on the HWBI (Figure 1). Decisions are pathways from actions to well-being so the cumulative weight of the links making up a pathway

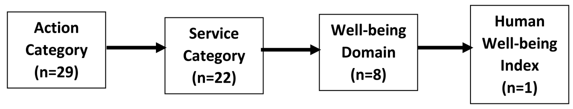

FIGURE 1
Lindemann spine diagram of decisional well-being network showing direction of influence flow from Action category nodes to the index of human well-being. Arrows do not indicate link weights between individual nodes.

represent its relative importance to the overall decision space. The eco-decisional network does not allow for flow in the opposite direction, nor does it consider cross flow within node type, such as influence of service nodes on each other. The latter is an important subject but not considered here. Weights can fall to zero effectively removing the influence between nodes. Weights are normalized influence scores (0-1) assigned individually to each link in the network (See below).

Link weights for the community specific eco-decisional networks were assigned to node and link types described above based on numerical output from workshop discussions (Figure 2; n=9) and the related keyword analysis (Fulford et al., 2017). Weights represent the cumulative results of relative importance estimates derived from group discussions and anonymous prioritization exercises (Community Comparison Report; https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHEERL&direntryid=330853), as well as direct count of how often connections were mentioned in analyzed documents (Fulford et al., 2017). All raw weight scores were normalized (0-1) within type (e.g., keyword counts) and consolidated across data types for each specific node-node link. Full details on weight derivations can be found in the Supplementary Data. Link weights for the random network analysis were assigned randomly (0-1) within network size which was defined by node count.

2.3 Measures of weighted network properties

Network properties can be described by comparison of individual paths (cumulative weight) through the network or using indices of overall network organization. For path comparisons, the focus is on cumulative connection strength between select action categories (potential decisions) and domains of human wellbeing (decision outcomes) with services acting as intermediary effects. Comparing paths can be as simple as relative weights for two alternative paths (which action is more influential on a specific well-being domain) or a more complex comparison examining relative effects of chosen actions on all domains of human wellbeing (decision trade off comparison across all domains). Network level indices describe overall organization, and the literature reports a suite of possibilities including those with origins in exergy (Jorgensen and Ulanowicz, 2009) and diversity (Ulanowicz et al., 2009) indices. Here we focus on the latter and apply a set of indices described by Zorach and Ulanowicz

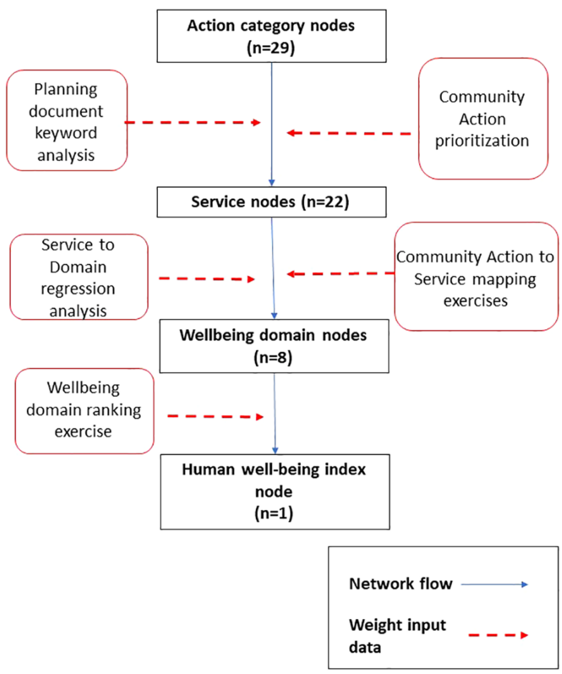

FIGURE 2
Flowchart summarizing determination of weights for node links by link type. Planning document keyword analysis was described in Fulford et al. (2017). Community action prioritization, Community actions to Services mapping exercises, and Well-being domain ranking exercises were conducted during stakeholder engagement described in the Supplementary Data section. All data were normalized (0-1) within link type for inclusion in the network analysis.

(2003) for weighted networks to analyze relative linkage weights to describe the balance between network connectivity and mutual path information. These indices are particularly useful for decision making as Zorach and Ulanowicz (2003) described how relations between network connectivity and number of realized roles (i.e., pathways) can be used to optimize flow across an entire network, and we use this concept here for maximization of influence on community well-being as a function of resource investment.

Ascendancy (A) – Ascendancy has been called the scaled mutual constraint (Ulanowicz et al., 2009) of a network and is generally the information content of a network (e.g., what does knowledge of node *i* tell us about node *j*)? in that higher Ascendancy indicates more network efficiency and therefore more dominant (higher weighted) connections. However, ascendancy has an upper limit or capacity, and as A approaches capacity, the network becomes less flexible and more sensitive to perturbation. In the case of the eco-decisional network this upper limit would be viewed as a dilution of influence or excess redundancy. Network capacity is considered fixed for eco-decisional networks as we describe them here.

Connectivity – This index is the weighted average of links per node which describes how connected the nodes are as a whole and includes both presence and importance of connections. Link counts per node vary between 0 and N-1 each with a weight between 0 and 1. Therefore connectivity (C) is a measure of both network size and organization. In an examination of natural ecological systems, Ulanowicz et al. (2009) described a window of vitality (WOV) in ecological networks for which connectivity ranged from approximately 1 to 3.01 for these 'natural' networks. Increasing connectivity increases redundancy in the network and reduces importance of individual paths.

Realized network roles – Roles are unique sets of paths through the network which can be interpreted as choices for achieving specific outcomes. A role can be shared completely or partially across multiple decisions pathways in that they each have similar influence on human wellbeing. This means that the number of realized roles (R) will increase with network size but also decrease with increased redundancy among pathways. An understanding of this redundancy across the whole network describes the amount of mutualism (Fath, 2007) across available pathways and how this redundancy affects network robustness (Fath, 2015). This metric describes how efficiently available resources like time and funds are being allocated to achieve objectives integrated into human well-being. The number of realized unique roles in a network are impacted by both link density and relative link weight in that large differences in weight will create more unique roles. Ulanowicz et al. (2009) in their analysis of natural systems reported their WOV had a range for realized roles between 2 and 4.5 across multiple networks. There is a balance between diversity of path options and redundancy that defines the overall information content of the network captured by network indices.

2.4 Random network analysis

Random network analysis was used to examine patterns in the relationship between described network-based indices and both network size and complexity. This approach builds on the random network analysis of Zorach and Ulanowicz (2003) and with a comparison of our network space to their 'window of vitality' describing the proposed bounds of connectivity and information content of ecological networks. Network size is defined based on combined value of node number and number and weight of existing links. Complexity was defined based on network indices of mean connectivity (C), Ascendancy (A), and Realized Roles (R) to measure patterns with network size and complexity and compare the outcome for our random networks to reported values from the literature as a tool for understanding observed patterns that can aid in defining the most efficient and robust structure for an eco-decisional network. We examined a random group of 500 networks ranging from n=20-100 nodes and from 0 to an upper limit of *n x n* links. The weight of each defined link was also randomly set between 0 and 1. The values of C, R, and A were examined across the range of sizes and compared to similar output reported by Zorach and Ulanowicz (2003). Comparisons were made graphically to published data and to examine relationships among indices associated with network size and complexity that can be used to interpret community-specific network data.

The random network analysis was conducted with three slightly different constraints reflecting three relationships with the community-specific eco-decisional network. The fully random network with varying size (i.e. node count) is described above and was used to describe the unconstrained pattern of network indices with size and to compare our results to those previously reported by Zorach and Ulanowicz (2003) in their 'window of vitality'. The second random network analysis was based on the same 60 node set used in the community specific analysis (Table 1) but with randomly assigned link weights with two levels of constraint. The community random network analysis was first run with links limited to all possible AC-S, S-D, and D-HWBI links, as in the community specific network. Link weights were varied randomly between 0 and 1 allowing for a maximum possible link count of 822. The second level of constraint limited links to the set used in the community specific network (287; See Supplementary Information) but with weights set randomly (0-1). The community decisional random network results were compared to both the full random network results as well as the community specific network results described below as a bridge between values of the network indices for the unconstrained and the constrained network outcomes.

2.5 Real world network comparison

Community specific network analysis was based on community-defined links between the 60-node set defined in Table 1. An eco-decisional network was built based on community engagement data defining weights (0-1) for nodes representing action categories, services, and domains of wellbeing. Link weights were assigned based on community data for relative importance (n=60; l ≤ 822; See Supplementary Information). This community specific network iteration represents the real-world decision space for an amalgamated community seeking to achieve improvements in stakeholder well-being by replacing a 'one decision at a time' approach with an integrated decision option.

Node and Edge selection and weighting – A series of workshops combined with a keyword analysis of community planning documents were previously described and used for both node identification and weighting in the community-specific network development. Edge weights were derived differently for each edge type (AC-S; S-D; D-HWBI).

Action category (AC) nodes represent potential actions or decisions to be made by a community seeking to improve human well-being as a path to increased sustainability. Action category nodes were identified by workshop participants in nine separate communities, compiled into an overall list, and combined with similar keyword-based results from 97 community planning documents. This list of specific actions was further consolidated into action categories based on an expert discussion of the original action list. The resulting action categories were used as nodes in the community specific eco-decisional network in order to maximize transferability across communities.

Service nodes (S) were identified with a national study on the impacts of Services on Domains of human well-being (Summers et al., 2016). These service categories were used as nodes in the community specific eco-decisional network but also cross-referenced with workshop and keyword analysis results to identify AC-S links (Figure 3A). Weights for identified AC-S were normalized (0-1) from priority voting results conducted during workshops and counts of service mentions in planning documents.

Domain nodes (D) were set based on the eight domains of human well-being based on the formal development of HWBI as an overall index of human well-being (Summers et al., 2014). Formal prioritization of the domains of human well-being were conducted during community workshops (Fulford et al., 2016) to estimate community priorities and set weights for identified S-D and D-HWBI links in the community specific eco-decisional network (Figures 3B, C). The national HWBI study also applied a regression approach to quantify relationships between services and HWBI domains and these regression results were used to standardize S-D link weights based on the workshop outcomes into a cumulative weight for each S-D link in the network (Figure 3D).

All domain nodes were linked to HWBI but could have varying weights. Weights on links between domain nodes and the HWBI node were estimated based on community discussions combined with group voting activities during workshops, which were designed to place the eight domains of HWBI into priority order. The results of the ranking exercises were normalized (0-1) to the maximum value reported and combined across the communities to obtain a composite set of D-HWBI link weights, which were used as weights in the community specific eco-decisional network analysis.

2.6 Analysis of community specific network based on network indices

Methods for community comparisons were explored as a methodology for defining optimal network organization around realized roles (R) and mean connectivity (C). Random network iterations of link weights (0-1) represent the theoretical bounds and patterns of change for network indices similar to the 'window of vitality' described by Zorach and Ulanowicz (2003). These bounds and patterns were compared to the realized community network's properties as a method for ranging differences among hypothetical communities.

3 Results

3.1 Random network analysis

A set of 500 networks with random size (n=20 to 100) and random link weights (0-1) were assembled and compared based on calculated values for the network indices (C, R, and A). The range of values were plotted and compared to published results for random networks in Zorach and Ulanowicz (2003). Random network results demonstrated a clear pattern between mean connectivity and realized roles with R highest at lowest connectivity and dropping rapidly with a cluster of values centered on the region referred to as the Window of Vitality (Figure 4). This demonstrates the pattern between R and originally described by Zorach and Ulanowicz (2003) for weighted networks. Pattern indicates relationship

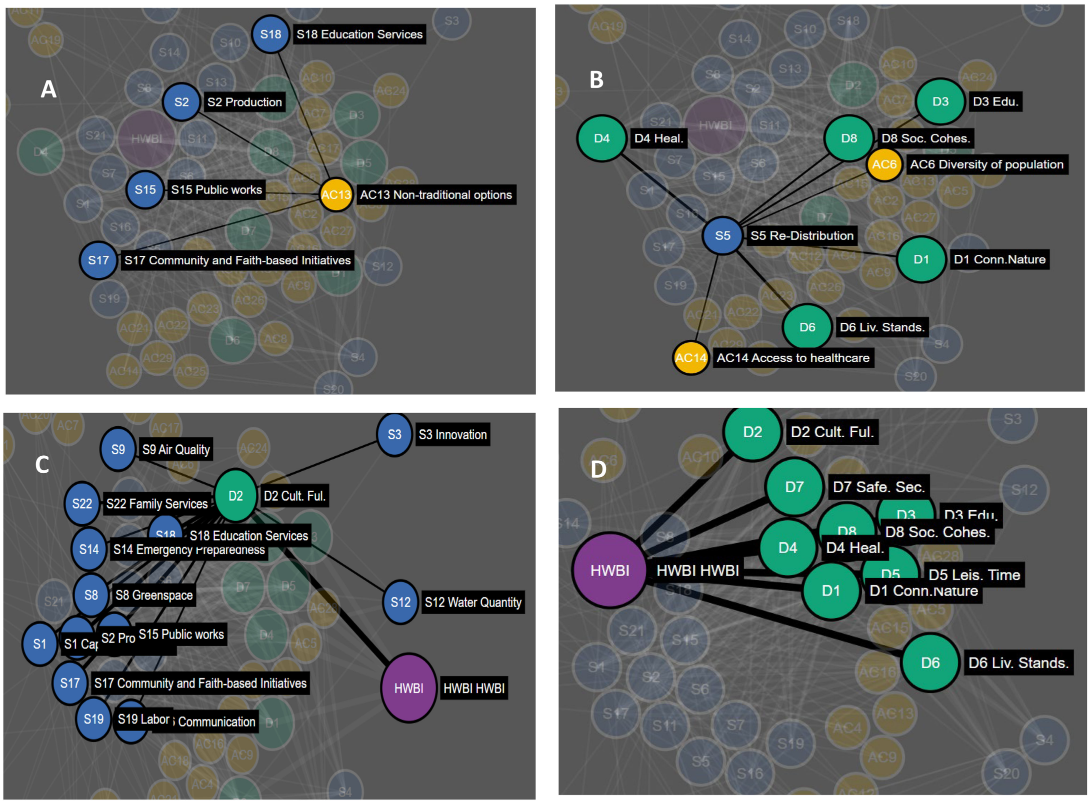

FIGURE 3
Decisional network diagram highlighting **(A)** Action category (yellow) to Service (blue) links. Example AC-S link shown is Non-traditional options linked to four service nodes: Community and Faith-based initiatives, Public works, Production, and Education services. Decisional network diagram highlighting **(B)** Service links to both Action category and Domains of human well-being (green). Example AC-S-D link shown is the Re-distribution service node linked to Action categories and Domains of human well-being. Decisional network diagram highlighting **(C)** Service nodes links to Domain nodes and the Human well-being Index node (purple). Example Domain of human well-being is D2. Cultural Fulfillment. Decisional network diagram highlighting **(D)** Domain node links to the Human well-being Index node (HWBI; purple). All Domain nodes are linked to the Human well-being index nodes as these are the eight Domains that combined to calculate HWBI. See Supplementary Information for full list of nodes by type.

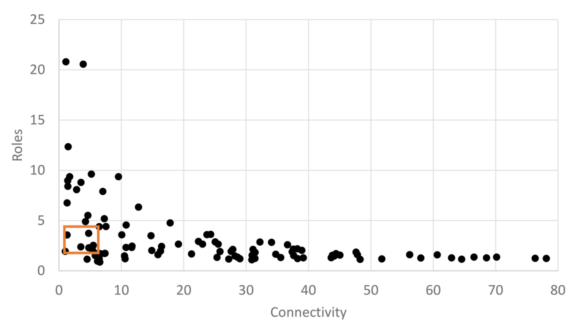

FIGURE 4
Scatter plot of mean connectivity (C) vs. realized roles (R) for a set of 500 random networks. Each network has a random node count (size; 0-100 nodes) and a random weight (0-1) for each link. Polygon shows 'Window of Vitality' described by Zorach and Ulanowicz, 2003, which brackets a set of real-world ecological networks.

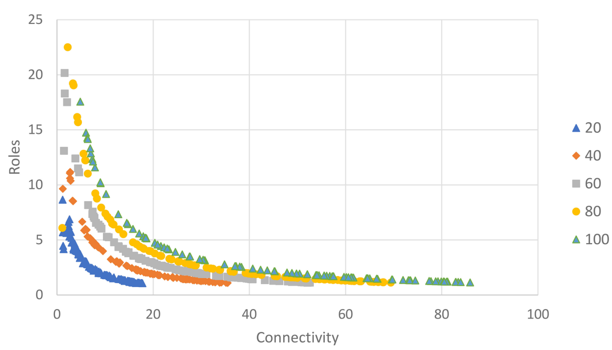

FIGURE 5
Scatter plot of mean connectivity (C) vs. realized roles (R) for a set of 500 random networks. Each network has a node count within a size group (100/group; node count = 20, 40, 60, 80, or 100) and a random weight (0-1) for each link. Data are plotted in size groups.

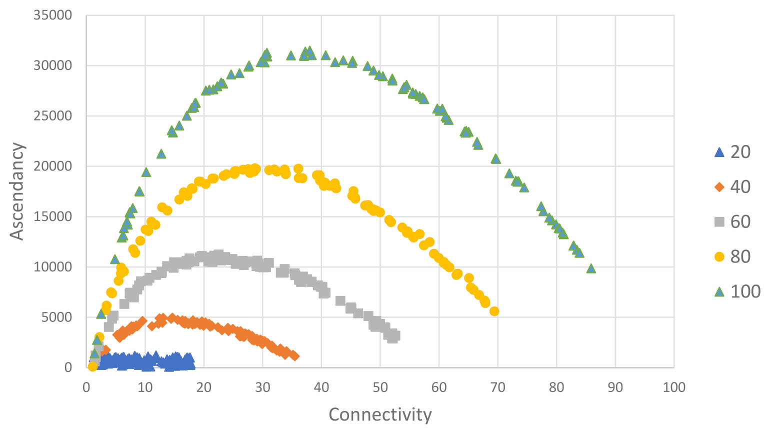

FIGURE 6
Scatter plot of network Ascendancy vs. Mean connectivity for 500 random networks delineated by network size (n=20-100) measured as number of nodes. Links randomly assigned weight between 0 and 1. See text for details.

between C and R with unique roles in the network dropping as connectivity increases.

If we delineate random networks into size groups (n=20, 40, 60, 80, 100) and replot the pattern between C and R takes distinct shape indicating that as link density (C) increases with a fixed node count, the relationship between connectivity and realized roles can be well described with a power law function. Realized roles is maximized at low connectivity for a given network size and initially drops rapidly as connectivity increases but approaches a minimum value for R for a given network size (Figure 5). For a fixed node size, the pattern is very consistent.

The relationship between the mutual information index, ascendancy, and mean connectivity was slightly different. Pattern with network size is also evident for our index of network mutual information (A) (Figure 6). The Ascendancy index has a parabolic relationship with mean connectivity indicating that network information about the described system increases at low connectivity but reaches a maximum and begins to decline as network redundancy increases. For instance, in the network size group (n=40), the maximum for A is reached at a C value of approximately 14.8 which is consistent with the C value at which the decline in number of roles begins to slow (Figure 5). The pattern is clearer for Ascendancy, but the Realized Roles (R) is a more understandable index of network value as roles represent decision pathways from Actions to Well-being.

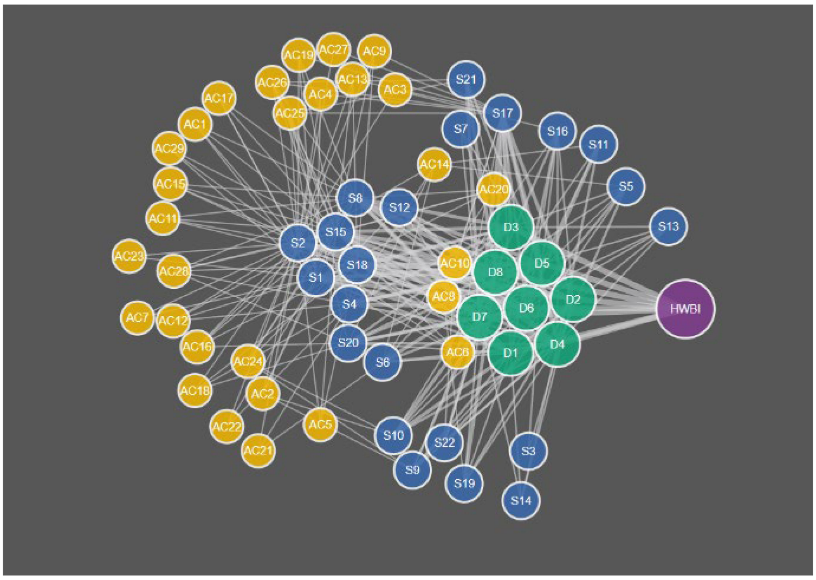

FIGURE 7
Diagram of whole community specific eco-decisional network structure including all nodes listed in Table 1 and Figure 1. Network nodes have four types: Action categories (yellow), Services (blue), Domains of human well-being (green), and HWBI index (purple).

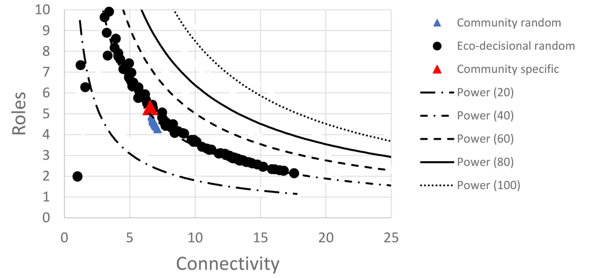

FIGURE 8
Scatter plot of random decisional network results for mean connectivity and realized roles showing power relationship for random network sizes between 20-100 nodes each (lines). Data points show distributions for 100 random eco-decisional networks with 64 nodes and either a maximum of potential links up to 822 (black circles), a restricted set of random links up to 287 (blue triangles), or the single community specific network with 64 nodes and 287 non-zero links (red triangle). See text for details.

3.2 Community specific network analysis

The second part of the analysis involved homing in on the node/edge structure of the eco-decisional network. The eco-decisional network includes 60 total nodes in three types (Action category, Service, and well-being domain, HWBI; Figure 7; Table 1), and the random network analysis for the eco-wellbeing network included weights assigned to 822 possible links in the unconstrained random test (AC-S, S-D, and D-HWBI links only), and 287 possible links in the random test limited to community specific links only (links identified during community engagement only; See Supplementary Information).

When the eco-wellbeing random network was compared to the results of the full random network analysis, the 60 node eco-wellbeing network showed a similar pattern for Realized Roles vs. mean Connectivity but better resembled the smaller (n=40) network than the random network of similar size (Figure 8). The random analysis of the restricted eco-wellbeing network, which was limited to 60 nodes and 287 links in three categories showed a similar pattern but represented a small subset of the unrestricted community network near the middle of the R vs. C range (Figure 9). Finally, the community specific network containing 60 nodes and link weights based on specific community input generated an R vs C value near the top of the restricted network range consistent with the overall range for the random network results (Figure 9 inset).

The community specific network (Figure 9) had a connectivity of 6.7 links per node and 5.3 realized roles from 60 nodes and 287 links between nodes. The community data were positioned at the upper end of the C vs. R curve for community data suggesting this is a maximum number of unique roles and a minimum connectivity. Likely shifts in the decisional network made through changes in relative weight of decisional pathways would therefore reduce unique pathways between action categories and human well-being and increase network redundancy.

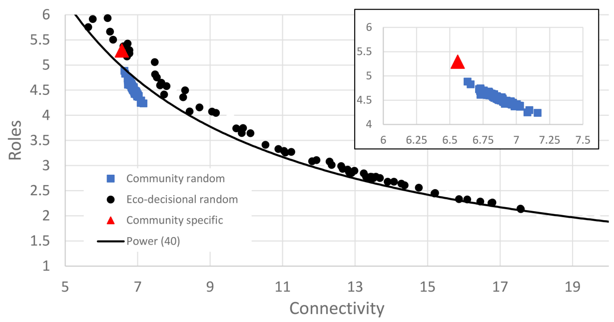

FIGURE 9
Scatter plot of random decisional network results for mean connectivity and realized roles showing power relationship for random network of size 40 for reference (black line). Data points show distributions for 100 random eco-decisional networks with 64 nodes and either a maximum of potential links up to 822 (black circles), a restricted set of random links up to 287 (blue triangles), or the single community specific network with 64 nodes and 287 non-zero links (red triangle). Inset figure shows eco-decisional data in more detail. See text for details.

4 Discussion

Network tools and analyses have been used to identify optimal organizational patterns in ecological, social, and hybrid networks. The value of understanding network organization is that information flow through networks can be optimized to achieve complex goals such as ecological/economic stability (Cumming et al., 2014; Huang and Ulanowicz, 2014), optimality of information flow in social networks (Butts, 2008; Henry et al., 2014), how network indices may inform important concepts like sustainability (Opsahl et al., 2010; Hu et al., 2017), and as we sought here a balance between decisional impact and redundancy of actions for integrated decision making.

Decisional science is largely a social discipline and there is a robust body of research on network theory as it pertains to social organization (Manning et al., 2014; Dykstra et al., 2016). However, the emphasis has largely been on unweighted network analysis intended to elucidate organization (Opsahl et al., 2010) and the process of network assembly (Butts, 2008) as factors in understanding social interactions. In contrast, ecological network analysis builds on material flow theory (Ulanowicz, 2001), and is intended to understand networks as a suite of interrelated throughput pathways that vary in importance but collectively follow similar organizational constraints as social networks (Lau et al., 2017). In a review of network analyses, Lau et al. (2017) considered both social and ecological network analyses and observed that integration across disciplines was possible but required common use of definitions and tools for analysis. Zorach and Ulanowicz (2003) in an attempt to generalize network theory based on ecological throughput presented an approach to applying throughput calculations such as Ascendancy to weighted networks and explored observed patterns in network complexity. Here, we have expanded on this approach to consider network organization as a tool for informing community decision making, where we observe similar pattern in the balance of realized roles (e.g., pathways through the network) and network complexity.

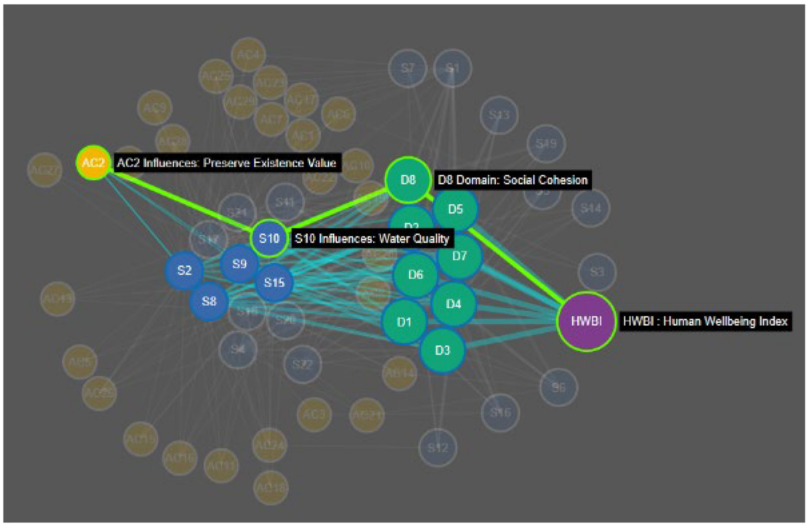

FIGURE 10
Example pathways analysis based on a community-specific eco-decisional network. Pathways are shown for connecting action category (Preserve existence value) to the index of Human well-being (HWBI) through affected service and HWB domains nodes. Bolded path is a theoretical chosen path (highest weight) for action considered in the context of all the other options.

Complex community decisions involve multiple potential actions and multiple paths to desired wellbeing outcomes. In our discussions with community stakeholders emphasis was placed on a shift from multiple independent decisions (e.g., economic development vs. public safety) towards an integrated approach that seeks common endpoints. In the example shown in Figure 10, there are multiple pathways from the Action Category (e.g., Preserve existence value of existing natural resources) to overall human well-being, but the most influential pathway passes through the Service 'Water quality' and the wellbeing domain 'Community cohesion'. In this example existence value means clean water, which yields a sense of community to the stakeholders. This is useful information for forging a decision, but other such dominant pathways can also be identified across the entire network and used both to understand their collective effect on wellbeing, but also identify the number of dominant pathways (Roles). According to our network analysis there should be no more than 6 Roles and this number could be reduced as low as 3 to maximize efficiency of effect on human well-being. Communities can use the eco-decisional network tool to focus their actions into the most efficient overall structure. This process is made less complex if we can identify the descriptive network structure, and both intermediate and final outcomes that are well-defined and measurable. This demonstration of an eco-decisional network tool can aid decision makers in making this shift by identifying relative roles and most influential paths from action categories to HWB Domains. General patterns highlighted in the random network analysis indicate that changes in community priorities, quantified as network link weights, can influence the range of network indices, which follow a power law function between impact of individual decisions and the redundancy of impacts across different decision pathways. Further the link constraints of the eco-decisional network result in network indices comparable to unconstrained networks of a smaller size (node count). These network characteristics affect outcomes in a predictable way and are adjustable based on a communities choices. Ascendancy has been described as the amount of information contained in a network tool (Ulanowicz, 2002) and in this case information is the different ways a suite of potential decisions may result in desired outcomes. Decision support is driven by such information and our analysis indicates that a maximum can be reached based on optimal values for network connectivity and realized roles.

The eco-decisional network is also useful for understanding trade-offs among potential decisional pathways as all paths in the network are defined in a comparable manner. These trade-offs become important when community decisions are made across multiple pathways with limited resources. Trade-offs highlighted between connectivity and number of unique roles capture the choice between trying to do a lot at once vs. choosing the most direct path to specific goals. Shifts in realized roles reflect the level of integration among decisions that is impacted by the level of connectedness among decisions. Therefore, changes in C and R for a community-specific eco-decisional network that are driven by how Action-Service-Domain of well-being links are defined reflect real world outcomes. This is consistent with similar network-based community analyses of sustainability (Bodini, 2012). Our analysis shows that as connectivity increases the real number of paths (roles) in the network drops rapidly and the decision space shifts from high impact through fewer specific pathways to a diverse outcome that may have wide impact but requires investment in many more action categories at once to achieve a desired outcome. This pattern is consistent with the stability-complexity debate in ecosystem network theory (Haydon, 1994), which is called network robustness by Ulanowicz et al., 2009. In their analysis of 'real-world' ecological networks, Zorach and Ulanowicz (2003) highlighted the 'Window of Vitality' as a generalizable pattern in network assembly observed across different network assemblies. The window of vitality concept has been broadened to examine similar patterns in economic networks (Zisopoulos et al., 2022). In a similar manner we observed a generalizable pattern in our analysis of real-world networks in the form of a power law function. Since this is a decisional network there is no absolute optimum but rather a range of choices to be made based on community priorities. That said the Ascendancy value of our community-specific eco-decisional network was well below the predicted optimum based on random network analysis suggesting there is room for improvement in information content of the network before the cost of redundancy is maximized.

The eco-decisional network can also inform a direct comparison of decisional pathways. Pathway trade-offs in the community-specific eco-decisional network will help inform priority setting not just for specific actions but across multiple actions that may not seem strongly related when examined in isolation. As an example, the action category (Preserve existence value) might be chosen as a decision category of interest intended to protect natural capital (e.g., streams) as a desirable feature of the landscape to community stakeholders based purely on its existence. Such benefits are hard to define in isolation, but the network can be used to show the multiple pathways by which an investment in existence value can yield an increase in services that are tied to HWBI (Figure 9). Once pathways are known then choices can be made as to the desired path(s) (e.g., investment in stream water quality) based on available resources, circumstances for early action, and its perceived impact. Most importantly, the chosen path of action can be compared in the network to other options in terms of relative impact so that the decision is driven not just by predicted outcomes but also by the opportunity cost of other possible outcomes. The optimality and consensus achieved in network development give structure to these trade-off comparisons as well as a clear visual and numeric method of communication, which is important for stakeholder acceptance.

In the example community described in the Supplementary Data and the associated report (Deeper Look at Ouachita river: https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=542172&Lab=CEMM), four action categories were defined and mapped to domains of human wellbeing to allow for development of a community eco-decisional network. Prior to network development the relative importance of these four action categories in terms of their impact on community objectives was not quantified and any trade-off decisions among the respective pathways was not definable. The development of the network tool allowed for the relative roles and connectivity to be quantified so that the optimal pathway to well-being was identified as investment in greenspace and dredging of the river. The exercise also identified several potential shifts in network weightings possible through changes in how action categories were carried out that would decrease the number of relative roles and therefore increase efficiency of actions influence on well-being. The resulting recommendations allowed for stronger advocacy of an integrated decision approach as the four action categories were evaluated together rather than independently.

As with all network tools resolution is a critical feature of overall organization that must be considered in developing and using network indices in any specific context. This is most readily apparent in ecological networks like food webs, which are sensitive to resolution choices in node definition that range from single nodes for each functional group (e.g., primary producers) down to species specific nodes that can result in large increases in complexity (Zorach and Ulanowicz, 2003). In the eco-decisional network this is reflected in the wide range of network indices resulting from changes in network size (i.e., node count; Figure 4). Yet, the choice to use Action categories, which allow for a range of specific actions to be reflected in a single node and the use of stakeholder input to define 'Action category' and 'Service' nodes added important structure to the network definition and greatly reduces the observed variability. Further, the application of the Human Well-Being Index (Summers et al., 2016), which was built on specific well-being domains, provides both conceptual and analytical structure to the desired endpoints for decision making. Connectivity and Realized Roles are tied to how we define AC, as well as influence of AC on services, which were defined through input across multiple communities and the identification of common ground between communities.

Networks help visualize relationships so that actions chosen do not contradict each other (tradeoffs) or accomplish similar things (redundancy in perceived roles vs. realized roles), and these trade-offs can be examined and optimized as a comparison of specific decision pathways in the context of the other options. These features exploit the theory of network analysis in a novel way that is accessible and can be tied to community input. Community-specific eco-decisional network tools are designed to aid community decision makers of all forms make the shift towards a common goal of improving stakeholder well-being. Eco-decisional well-being networks can also be adapted to specific community goals and compared across community types (Fulford et al., 2015) to better inform integrated decision making. It is also important that networks provide a repeatable framework. Lau et al. (2017) highlighted the need for reproducibility and meaningful benchmarks for comparison, and our network approach was designed to be highly transferable across communities and integrated across issues of interest. Future work will involve development of visualization tools and more quantitative pathway analysis so that these features of networks can also be applied to specific community decision making.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found here: EPA ScienceHub, https://catalog.data.gov/harvest/epa-sciencehub.

Author contributions

RF conducted the data analysis and contributed to the writing of the manuscript EP developed the network visuals help conduct the analysis and contributed to the writing of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Identifying priority ecosystem services in tidal wetland restoration

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Classification systems can be an important tool for identifying and quantifying the importance of relationships, assessing spatial patterns in a standardized way, and forecasting alternative decision scenarios to characterize the potential benefits (e.g., ecosystem services) from ecosystem restoration that improve human health and well-being. We present a top-down approach that systematically leverages ecosystem services classification systems to identify potential services relevant for ecosystem restoration decisions. We demonstrate this approach using the U.S. Environmental Protection Agency's National Ecosystem Service Classification System Plus (NESCS Plus) to identify those ecosystem services that are relevant to restoration of tidal wetlands. We selected tidal wetland management documents from federal agencies, state agencies, wetland conservation organizations, and land stewards across three regions of the continental United States (northern Gulf of Mexico, Mid-Atlantic, and Pacific Northwest) to examine regional and organizational differences in identified potential benefits of tidal wetland restoration activities and the potential user groups who may benefit. We used an automated document analysis to quantify the frequencies at which different wetland types were mentioned in the management documents along with their associated beneficiary groups and the ecological end products (EEPs) those beneficiaries care about, as defined by NESCS Plus. Results showed that a top combination across all three regions, all four organizations, and all four tidal wetland types was the EEP naturalness paired with the beneficiary people who care (existence). Overall, the Mid-Atlantic region and the land steward organizations mentioned ecosystem services more than the others, and EEPs were mentioned in combination with tidal wetlands as a high-level, more general category than the other more specific tidal wetland types. Certain regional and organizations differences were statistically significant. Those results may be useful in identifying ecosystem services-related goals for tidal wetland restoration. This approach for identifying and comparing ecosystem service priorities is broadly transferrable to other ecosystems or decision-making contexts.

KEYWORDS
ecosystem services, tidal wetlands, restoration, document analysis, prioritization

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1 Introduction

Multiple reasons for conducting ecosystem restoration have been documented in the literature and in community-specific planning reports for decades, including improving coastal fisheries (Silva et al., 2019), mitigating climate change (Stickler et al., 2009), and supporting sustainable development goals of water conservation and food production (Adams et al., 2016; Gao and Bian, 2019). Although biodiversity, conservation, and ecological integrity are defined as primary goals of *ecological* restoration, they can also produce co-occurring benefits for people, and moreover, *ecosystem* restoration can aim solely at delivery of ecosystem services (Gann et al., 2019), defined as the outputs of nature that contribute to human well-being (Munns et al., 2015). In many cases, restoration plans have broadly stated goals to improve benefits to people interacting with the restoration site; yet those benefits are not explicitly defined or measured in most restoration monitoring programs (reviewed in Jackson et al., 2022). Instead, pre-restoration planning, monitoring, and restoration outcomes typically focus on the condition of ecological or biological structures or functions, as opposed to site uses or benefits to people. As a result, investments in restoration activities may fail to galvanize public support or achieve desired beneficial use outcomes (Benayas et al., 2009; Meli et al., 2014).

An essential first step to inform restoration planning and implementation at local to regional to national scales involves more explicit recognition of which ecosystem services are restoration priorities or likely to be affected by restoration activities. A consideration of ecosystem services can facilitate conversations about what benefits to people may be gained or lost due to changes in the ecological condition (i.e., to vegetation, fauna, soil, water quality, etc.) at an area of interest (DeWitt et al., 2020). Ecosystem services can inform prioritization of the ecosystem management (i.e., development, protection, restoration) of resources by revealing how people use and benefit from natural versus developed lands in those areas. Ecosystem services can also help site managers communicate progress in language relatable to stakeholders and the public. Given that restoration is expensive, those charged with managing and protecting natural resources (e.g., state and federal agencies, conservation organizations, land stewards) have to make difficult spending decisions that should include assessing and monitoring the benefits of the natural resources being protected or restored (Daoust et al., 2014). Therefore, in our view, ecosystem services should be a part of the ongoing discussion of ecosystem protection and restoration.

However, leaving relevant ecosystem services out of the discussion can lead to restoration decisions that neglect commonly shared benefits to people, are disconnected from what matters to gain public support, or undermine community or management goals (Sharpe et al., 2020). The first step of any effort to examine how a geographically specified site's condition affects the production of ecosystem services, is to identify those services that could be (or are) produced at the site. Since that could be a long list, the second part of that effort is to prioritize which ecosystem services are of greatest interest to people who are managing, restoring, or using the site. In particular, a beneficiary-focused approach to identifying ecosystem services can help ensure direct relevance to people because these approaches explicitly connect biophysical attributes of nature to the people who use or care about them (DeWitt et al., 2020). The National Ecosystem Services Classification System Plus (NESCS Plus; Newcomer-Johnson et al., 2020) codifies this approach by classifying ecosystem services into three components (i.e., a triplet): an environment type (i.e., the classification of where the ecosystem service is produced); a beneficiary or user (i.e., a classification of the role(s) people take while interacting with nature, by which a benefit is obtained); and an ecological end product (EEP) (i.e., the attribute of nature from which the benefit is derived). For example, a wetland (environment type) provides fish (EEP) to recreational anglers (beneficiary).

Tidal wetland areas are inundated or saturated periodically by tidally driven waters at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation, fauna, soil types, and microbiota typically adapted for these hydrologic conditions (Cowardin et al., 1979). Tidal wetlands provide numerous ecosystem services to people living in coastal communities, including flood protection, and the loss or degradation of these habitats can diminish the production of ecosystem services and the health, economy, and well-being of coastal communities (Barbier et al., 2011; Engle, 2011; Gilby et al., 2020). Tidal wetlands have been subject to centuries of exploitation (e.g., for agriculture and materials extraction), development (e.g., commercial and home construction, roads and other infrastructure), and degradation (e.g., chemical contamination, nutrient runoff, invasion by non-native species), leading to substantial loss globally, nationally, and regionally (Dahl, 1990; Kennish, 2001; Brophy et al., 2019). Furthermore, rising sea levels and intense coastal storms driven by climate change also diminish the size and condition of tidal wetlands (Cherry and Battaglia, 2019) and these impacts are forecast to increase.

Organizations conducting wetland restoration mention the importance of ecosystem services (e.g., Mobile Bay National Estuary Program (MBNEP), 2013, South Slough National Estuarine Research Reserve (NERR), 2017, and Maryland Department of the Environment (MDE), 2018); however, often they do not include an explicit prioritization element (Diefenderfer et al., 2009) or connections to people or human well-being. Regional identities can exert a strong influence on local perceptions and restoration priorities, driven by shared social and recreational customs, shared histories of land use planning and political decisions, or economic and funding priorities (Cook et al., 2012; Borgstrom et al., 2016). Moreover, organizations operate under different mandates, authorities, jurisdictions, time scales, and constraints, but may share overarching goals (Jackson et al., 2022). To identify which ecosystem services are of greatest priority to the tidal wetland restoration community, we utilized a keyword-search approach using tidal wetland management documents to determine which ecosystem services were mentioned most frequently across documents, the organizations that published the documents, and the U.S. regions where the tidal wetlands occurred. We focused on using "gray literature" management documents as we believed these would more likely identify the multitude of ways that a given tidal wetland provide benefits to people using it, as understood by people managing the wetland. We assessed priority among EEPs, beneficiaries, and tidal wetland types by the frequency each was mentioned across documents. Because of the importance of tidal wetlands to coastal communities and the substantial management efforts to protect and restore these wetlands by local, regional, and federal organizations, the results of this analysis may inform restoration, conservation, or climate adaptation planning decisions. The results may be used by tidal wetland site managers to set management goals (i.e., which ecosystem services to restore or protect) and/or for selecting ecosystem services-based metrics for site condition monitoring and assessment. Moreover, the classification system and assessment approach are broadly transferrable and can be used to identify and compare ecosystem services priorities for other ecosystems or decision-making contexts.

This project presents a top-down, literature content-analysis approach to identify beneficiaries or users of tidal wetlands and prioritize ecosystem services of greatest relevance to them, based on extracting information from existing documents (e.g., Yee et al., 2019). Our specific objectives were to: 1) obtain tidal wetland management documents from the gray literature; 2) create a searchable list of ecosystem services keywords based on NESCS Plus (Newcomer-Johnson et al., 2020) and the National Wetland Inventory (Cowardin et al., 1979) as a consistent and objective means for classifying tidal wetland types, beneficiary groups, and EEPs in the documents; 3) quantify the frequency that ecosystem services triplets (i.e., tidal wetland type, beneficiary group, EEP) were mentioned across management documents using an automated document search to identify co-occurring keywords; and 4) compare the number of mentions of ecosystem services across regions, organizations, and tidal wetland types to identify patterns of priority ecosystem services.

2 Methods

The document analysis used in this project was based on an approach and automated search described in Yee et al. (2019) that focused on identifying ecosystem services triplets. Each of the triplet components had classes and subclasses that were defined by their own set of synonymous keywords. To be considered a positive hit for an ecosystem services triplet within a document, keyword matches to all three triplet components had to co-occur within a single sentence, also checking the prior 1–2 and following 1–2 sentences if necessary. The analysis produced a list of ecosystem services triplets, which were prioritized by frequency of occurrence across documents within the set of identified tidal wetland management literature. Those ecosystem services mentioned most frequently across documents were assumed to be of greatest general interest to the restoration community (i.e., wetland restoration managers charged with representing beneficiary interests) represented by the documents analyzed, and consequently given priority ecosystem services status.

The general identification and assessment approach follows four steps:

- Step 1. Obtain tidal wetland management documents from the gray literature;
- Step 2. Create a searchable list of ecosystem services keywords to classify document language by tidal wetland types, beneficiary groups, and EEPs based on NESCS Plus (Newcomer-Johnson et al., 2020) and the National Wetland Inventory (Cowardin et al., 1979);
- Step 3. Quantify the frequency that ecosystem services triplets were mentioned across management documents using an automated document search, developed in R (R Core Team, 2022), to identify co-occurring keywords; and
- Step 4. Compare the number of mentions of ecosystem services across regions, organizations, and tidal wetland types to infer priority ecosystem services.

2.1 Step 1: Obtain tidal wetland management documents

We sought to evaluate the degree to which ecosystem services provided by different types of tidal wetlands differed among coastal regions of the United States and among different management-organization categories. The focus of this project was on three coastal regions:

- **Pacific Northwest** (Oregon and Washington);
- **Mid-Atlantic** (Virginia Beach, Virginia, to Ocean City, New Jersey); and
- **Northern Gulf of Mexico** (Louisiana to Apalachicola Bay, Florida)

Within these three regions, a gray literature search was conducted to obtain management documents from organizations that have tidal wetland stewardship missions. The literature included conservation plans, restoration and/or monitoring plans, and property and/or habitat management plans. The compilation and analysis were conducted using gray literature because such reports would likely comprehensively discuss the ecosystem services valued by stakeholders or users of the tidal wetland properties. In contrast, scientific journal articles on tidal wetland conservation, restoration, or management typically focus on a subset of possible ecosystem services germane to addressing specific research questions and may reflect the interest of the investigators to a greater degree than those of stakeholders. It should be noted that the restoration documents reviewed typically did not specify whether community input was used when developing each restoration plan, so these documents may primarily reflect the managers' priorities as representatives of the beneficiaries in their community. The four categories of organizations included:

- **Federal agencies** (i.e., agencies that manage or restore tidal wetlands on federal property);

- **State and local agencies** (i.e., agencies that manage or restore tidal wetlands on State, County, or City/Town/Township property);
- **Land stewards** (i.e., private and non-governmental organizations that own tidal wetland properties and manage them to sustain natural ecological structure and function); and
- **Wetland conservation organizations** (i.e., private or non-governmental organizations that promote or fund wetland conservation, restoration, or management).

A list of organizations involved with tidal wetland management within these regions and categories was created through expert knowledge of the members of the research team and expert knowledge of colleagues of team members (inside and outside their respective affiliations) located in each geographic region (see Supplementary Material Data Sheet 4 for a full list of organizations). Documents had to be publicly available and accessible on organizations' websites. Searches within the websites involved two avenues: 1) a search using terms such as ("tidal" or "coastal") and/or "wetland" and/or ("management" or "conservation" or "restoration"); and 2) reviewing the website contents for programs or departments related to environmental work. The full document list was reviewed by all co-authors to identify potential missing documents. From there, one document was chosen for each organization per coastal region in order to equally represent each organization in the analysis. Document choice was based first on maximizing consistency among branches of a given organization (e.g., the Comprehensive Conservation and Management Plan (CCMP) for the National Estuary Programs) and secondly on recency of publication date. A total of 141 documents were used in the literature analysis (Table 1).

2.2 Step 2: Create a searchable list of ecosystem services keywords

The list of tidal wetland classes and subclasses was derived from the National Wetland Inventory (Cowardin et al., 1979) (Table 2A). Beneficiary classes and subclasses were derived from NESCS Plus (Table 2B; Newcomer-Johnson et al., 2020). The EEP classes in NESCS Plus are fairly coarse (e.g., Flora, Fauna), so more detailed subclasses were derived from a tool closely related to NESCS Plus, the Final Ecosystem Goods and Services (FEGS) Scoping Tool (Table 2C; Sharpe et al., 2020).

To ensure consistency in management document review, an automated process using an R-script (see Supplementary Material Data Sheet 1 for code) was used to search each document for triplet components. Given that management documents did not always use the same terminology, particularly considering differences between the study regions, a list of synonymous keywords was developed (modified from Yee et al., 2019) for each triplet component class and subclass listed in Tables 2A–C (see Supplementary Material Data Sheet 3 for the full list of keywords). Keywords could be paired with companion words (Table 3) such that both the keyword and the companion word had to be found in the same sentence (i.e., "AND" as a Boolean operator) in order to have a positive hit for that class or subclass. In most cases, keywords were also paired with exclude words, such that co-occurrence of both the keyword and the exclude word in a single sentence would not be considered a positive hit for that class or subclass (i.e., "BUT NOT" as a Boolean operator). Keywords, companion words, and exclude words were developed through an iterative process of examining preliminary search results and determining when unrelated results were found (i.e., false hits) or anticipated matches based on manual reviews of document text were missing. A final manual review of a random selection of document text was compared to automated results as a final check of consistency.

2.3 Step 3: Quantify frequency of ecosystem services mentions across documents

Once the documents were gathered and the searchable list of keywords defined, the R-script was used to conduct an automated search for the ecosystem services triplet components in the documents. The R-script read each document and assigned any sentence to a particular class or subclass of tidal wetland, beneficiary, or EEP, if that sentence contained valid keywords representing that class or subclass. The next step was to identify

TABLE 1 Number of documents analyzed in the literature analysis per organizational category per region.

Organization Categories	Pacific Northwest	Mid-Atlantic	Northern Gulf of Mexico	Total
Federal Agencies	5	5	10	20
State and Local Agencies	13	18	14	45
Land Stewards	17	23	16	56
Wetland Conservation Organizations	10	4	6	20
Total	45	50	46	**141**

TABLE 2A Tidal wetland classes and subclasses.

Tidal Wetland Classes	Tidal Wetland Subclasses
Tidal wetland	Tidal wetland unspecified
Emergent wetland	Emergent wetland unspecified
	Brackish or salt marsh
	Emergent tidal fresh wetland
Forested wetland	Forested tidal wetland
	Mangrove
Scrub-shrub wetland	Scrub-shrub wetland

TABLE 2B Beneficiary classes and subclasses.

Beneficiary Classes	Beneficiary Subclasses
Agricultural	Agriculture (general)
	Livestock Grazers
	Agricultural Processors
	Aquaculturists
	Farmers
	Foresters
Commercial and Industrial	Commercial & Industrial (general)
	Commercial Food Extractors & Fisheries
	Commercial Timber/Fiber/ Ornamental Extractors
	Commercial/Industrial Processors
	Pharmaceutical & Supplement Suppliers
	Commercial Fur/Hide Trappers
	Private Energy Generators
	Private Water Plant Operators
	Commercial/Industrial Property Owners
Government, Municipal, Residential	Government, Municipal, Residential (general)
	Public Water Plant Operators
	Residential Property Owners
	Military & Coast Guard
	Public Energy Generators
	Public Property Owners
Commercial/ Military Transportation	Nonspecific Commercial/ Military Transportation
	Transporters of Goods
	Transporters of People
Subsistence	Nonspecific Subsistence

(Continued)

TABLE 2B Continued

Beneficiary Classes	Beneficiary Subclasses
	Water Subsisters
	Timber/Fiber/Fur Subsisters
	Building Material Subsisters
	Food/Medicinal Subsisters
Recreational	Recreation (general)
	Experiencers/Viewers
	Food Pickers/Gatherers
	Recreational Hunters
	Recreational Fishermen
	Waders & Swimmers & Divers
	Recreational Boaters
Inspirational	Nonspecific Inspirational
	Spiritual & Ceremonial Participants
	Artists
Nonuse Value	Nonuse Value (general)
	People Who Care (Existence)
	People Who Care (Option[1]/Bequest)
Humanity	Humanity & Public Health

[1]The option for future generations to use, enjoy, or appreciate the existence of the good or service (Newcomer-Johnson et al. 2020).

TABLE 2C EEP classes and subclasses.

EEP Classes	EEP Subclasses
Flora	Flora (general)
	Flora Community
	Edible Flora
	Medicinal Flora
	Keystone Flora
	Charismatic Flora
	Rare Flora
	Commercially Important Flora
	Culturally Important Flora
	Pest/Invasive Flora
Fungi	Fungi (general)
	Fungal Community
	Edible Fungi
	Medicinal Fungi
	Keystone Fungi
	Charismatic Fungi

(Continued)

TABLE 2C Continued

EEP Classes	EEP Subclasses
	Rare Fungi
	Commercially Important Fungi
	Culturally Important Fungi
	Pest/Invasive Fungi
Fauna	Fauna (general)
	Bait Fauna
	Charismatic Fauna
	Commercially Important Fauna
	Edible Fauna
	Fauna Community
	Fauna for Fur/Hide/Trophy
	Keystone Fauna
	Medicinal Fauna
	Pest/Invasive Fauna
	Pollinating Fauna
	Rare Fauna
	Spiritually/Culturally Important Fauna
Soil	Soil (general)
	Soil Quality
	Soil Quantity
	Substrate Quality
	Substrate Quantity
Water	Water (general)
	Water Quality
	Water Quantity
	Water Movement/Navigability
Atmosphere/Weather	Atmosphere/Weather (general)
	Air Quality
	Wind Strength & Speed
	Precipitation
	Sunlight
	Temperature
Natural Materials	Natural Materials (Sand/Rock) (general)
	Fuel Quality
	Fuel Quantity
	Fiber Material Quality
	Fiber Material Quantity
	Mineral/Chemical Quality

(Continued)

TABLE 2C Continued

EEP Classes	EEP Subclasses
	Mineral/Chemical Quantity
	Ornamental Natural Materials (Shells/Bone)
Multiple Ecosystem Components	Multiple Ecosystem Components (general)
	Aesthetic Sounds & Scents
	Aesthetic Viewscapes
	Naturalness
	Aesthetic Open Space
Regulating Services	Regulating Services (general)
	Climate & Carbon Regulation
	Air Quality & Atmospheric Regulation
	Water Quality Regulation (Nutrients & Retention)
	Soil & Sediment Regulation
Risk of Extreme Events	Risk of Extreme Events (general)
	Risk of Flooding
	Risk of Fire
	Risk of Extreme Weather Events
	Risk of Earthquakes & Landslides

possible triplets for each sentence by generating all possible combinations of tidal wetland, beneficiary, and EEP classes or subclasses assigned to that sentence. If one of the three components of a triplet was not assigned to a sentence, first one and then two prior or following sentences were also checked for the missing component. If a particular component could not be assigned to a class or subclass, it was assigned as unspecified or unknown. All three components were required for a sentence to be assigned an ecosystem services triplet, and a single sentence could be assigned multiple ecosystem services triplets. This process generated a list of all possible ecosystem services triplets derived from each document. From there, co-authors manually reviewed each ecosystem services triplet to generate a master list of valid triplets based on examining examples of document language and verifying whether the specific combination of tidal wetland, beneficiary, and EEP was indeed representative of document intent, and not just an arbitrary combination.

The quality control process for document analysis was an iterative process that checked: (1) for missing concepts that did not get assigned to a triplet component and needed to be added to the keyword list; (2) for false hits that could be minimized with additional paired companion words or exclude words; (3) that the most likely ecosystem services triplets assigned to each sentence were indeed applicable to that sentence; (4) that valid ecosystem services triplets were not being excluded; and (5) that invalid ecosystem services triplets (i.e., arising from non-sensical

TABLE 3 Examples of tidal wetland subclass, beneficiary class, and EEP class keywords, companion words, and exclude words from the search term list.

Class/Subclass	Keywords	Companion Words	Exclude Words
Tidal Wetland Subclass	Keywords	Companion Words	Exclude Words
Tidal Wetlands Unspecified	tidal wetland; tidal marsh; tidal swamp	N/A	nontidal; subtidal; inland; freshwater; lake; river; stream
Forested Tidal Wetland	forested wetland; wooded swamp; hammock; woodland	tidal; coast; coastal; salt; saline; estuary	nontidal; subtidal; inland; freshwater; lake; river; stream; beach; dune
Mangrove	mangrove; mangroves	N/A	nontidal; subtidal; inland; freshwater; lake; river; stream
Emergent Wetland Unspecified	emergent wetland; emergent marsh; marshland	tidal; coast; coastal; salt; saline; estuary; bay; brackish	nontidal; subtidal; inland; freshwater; lake; river; stream
Brackish or Salt Marsh	salt marsh; salt hay; brackish marsh	N/A	N/A
Emergent Tidal Fresh Wetland	tidal fresh wetland; tidal river; tidal freshwater marsh; tidal fen	N/A	nontidal; subtidal; inland; freshwater; lake; river; stream; beach
Scrub-shrub Wetland	scrub shrub; shrub swamp; willow; saltbush; orach	tidal; coast; coastal; salt; saline; estuary; bay; brackish	nontidal; subtidal; inland; freshwater; lake; river; stream
Beneficiary Class	Keywords	Companion Words	Exclude Words
Agricultural	agriculture; fertilizer; pesticide; fungicide; herbicide; insecticide	N/A	agriculture department; non-agricultural
Commercial & Industrial	commercial; industrial; business; commerce	N/A	commercial fish; commercial pilot; commercial vessel; recreational industry; noncommercial
Government and Municipal and Residential	government; municipal; village; county; town; city; public use	N/A	legend; capacity; publicity; publication
Commercial/ Military Transportation	ship; vessel; air; rail; pilot; captain; navigation; train; navigability	transport; commercial	relationship; sediment transport; shipping; freight; commodity; container
Subsistence	subsistence; tribal; indigenous people; sustenance; traditional use	resource; use; survive	because; horticulture; agriculture; alternative; non-native
Recreational	recreation; vacation; amenities; visitor; tourist	N/A	research; science; student; teach; visiting wildlife; flower-visiting
Inspirational	inspire; cultural significance; cherish; treasure; wonder; beauty	N/A	treasurer; meadow beauty; spring beauty; beautyberry
Learning	learn; museum; visitor center	N/A	lessons learned
Nonuse	non-use; nonuse; non use	resource; opportunity; value	N/A
Humanity	humanity; everyone; humankind; all ages; all people	N/A	activit
EEP Class	Keywords	Companion Words	Exclude Words
Flora	flora; plant; flower; grass; kelp; seaweed; algae; algal; vegetation	benefit; bequest; children; comfort; goods; conserve	processing plant; aguirre plant; planting; grassroot; grass-root
Fungi	fungus; fungi; mushroom	benefit; bequest; children; comfort; goods; conserve	fungicide; chemical; oak death; mushroomed; agency; pickerel; by-product
Fauna	animal; fauna; wildlife; mammal; bird; reptile; amphibian; fish; insect	benefit; bequest; children; comfort; goods; conserve	toad flax; goosefoot; snowbird; geoduck; domestic animal; production of animal
Soil	sediment; soil; dirt; mud; clay; loam; stones; rocks; peat; substrate	accommodate; activity; aesthetic; allure; appeal; amaze; amenity	infertile; unproductive; disturbed; anaerobic; drainfield; retention; buffer; infiltration; runoff
Water	water	accommodate; activity; aesthetic; allure; appeal; amaze; amenity	agency; pickerel; by-product; especial; laboratory observ; field
Atmosphere	atmosphere; weather; climate; cloud; summer; fall; winter; spring	allure; amaze; appreciate; beauty; comfort; desired	rural atmosphere; changing climate; welcoming atmosphere; cloud berry

(Continued)

TABLE 3 Continued

Class/Subclass	Keywords	Companion Words	Exclude Words
EEP Class	Keywords	Companion Words	Exclude Words
Other Natural Components	natural material; natural object; aquatic material	accommodate; amenity; benefit; buy; collect; commodities	clay brook; sand dollar; stone lab; fossil fuel; sand barrier; sticker
Composite	nature; environment; ecosystem; coastal; landscape; grass; farmland	accommodate; amenity; benefit; buy; collect; commodities	landfill; product; goods; environmentally; orthophotograph; bay scallop; agency
Regulating or Buffering	nitrogen; carbon; air; atmosphere; water; sediment; erosion; aquatic	sink; replenish; sequestration; remove; improve; filter; buffer	pollut; total nitrogen loading; goal; plan; implement; problem; impact; challenge
Extreme Events	buffer; filter; control; protect; retention; attenuate; mitigate	extreme event; natural disaster; natural hazard	control survey

Keywords that did not need companion or exclude words are marked with N/A.

combinations of ecosystem services triplet elements) would be culled from the master list of ecosystem services triplets. An example of a non-sensical triplet is brackish or salt marsh, hunters, and fiber material quantity; this would be excluded because hunters do not target fiber material, whereas beneficiaries such as subsisters do target fiber material.

First, the code was run on a randomly selected set of 10 documents. The results were manually checked by reviewing at least two randomly selected example paragraphs per document containing the associated keyword. Any non-sensical hits (e.g., "currently" instead of "current" for the water movement EEP) were addressed with changes to the keyword list and the code was re-run on a new set of randomly selected 10 documents as needed until non-sensical hits were no longer returned.

Second, in an independent verification, automated results from the code were compared to results gathered by four people (two team members and two non-team members) familiar with ecosystem services concepts, using a random sample of documents and pages. The readers had access to the main class and subclass list but not the associated keywords. If the reading caught missing or invalid ecosystem services triplets, the keyword list was revised. Any necessary changes to the keyword list were made until any further iterations produced minimal changes to the final ecosystem services triplet counts across documents (i.e., <10% change in counts).

Once the keyword list was finalized, the code was run on the full set of 141 documents. Each combination of ecosystem services triplets was manually checked by reviewing at least two example paragraphs assigned to that triplet, randomly drawn from all documents. Any false hits, typically arising from multi-concept sentences (e.g., "hunting, agriculture, and fishing") were excluded from the master ecosystem services triplets list.

2.4 Step 4: Compare ecosystem services among regions, organizations, and tidal wetland types

The document analysis was used to identify the frequency with which ecosystem services triplets were mentioned in association with different tidal wetland types for each region and organization. Because documents varied widely in length and structure, the analysis used a presence/absence approach to determine whether a particular ecosystem services triplet was mentioned anywhere within each document. The analysis did not assess the number of sentences in which an ecosystem services triplet was mentioned. Importance of each ecosystem services triplet was then quantified as the percent of documents mentioning that particular class or subclass. For purposes of the analysis, if an ecosystem services triplet was mentioned in a document, then it was assumed that the triplet was "important," regardless of whether it was specifically identified as a component of a management goal.

The number of documents mentioning specific EEP and beneficiary subclasses, and EEP-by-beneficiary class combinations, was analyzed across regions, organizations, and tidal wetland types using the general linear model. For EEPs and beneficiaries, a generalized linear mixed model (GLMM; Proc GLIMMIX, SAS Institute Inc., 2023) analysis of variance (ANOVA) with multiple comparison of means was used to test differences between regions, organizations, and tidal wetland types. For EEP-by-beneficiary combinations, a similar GLMM (Proc GENMOD, SAS Institute Inc., 2023) was used to test the differences between regions, organizations, and tidal wetland types. Proc GENMOD was also used to assess whether higher priority assignments of EEPs or beneficiaries could be an artifact of document length (i.e., regions or organizations with longer documents were more likely to mention ecosystem services concepts than those with more concise documents).

3 Results

In total, more than 5,400 valid combinations of ecosystem services triplets were identified among the 141 documents. The search identified an additional 441 valid combinations where the beneficiary was unspecified (e.g., "potential to reach the local community"). The length of the documents ranged between 4 and 1,218 pages. Among organizations, the documents differed in length ($p=0.0002$) but a length difference did not occur among regions ($p=0.553$). See Supplementary Material Table 1 and Data Sheet 2 for summary results and data for all of the statistical tests performed. For each sub-section below, we pose a leading question to guide the analysis of the data.

3.1 Do EEPs differ among region, organization, or tidal wetland type?

All but 11 of the 71 possible EEP subclasses were mentioned in at least one document (Figure 1); 10 of those not mentioned fell under the fungi class, which indicates that fungi were not a priority in tidal wetland management. The only fungi subclass mentioned was pest/invasive fungi paired with beneficiaries such as agricultural, researchers, and residential property owners. The example paragraphs mentioning pest/invasive fungi referenced mold and fungi killing and/or reducing plant growth. Fuel quality was also not mentioned in any documents; paragraphs containing hits for fuel quantity would mention exploiting forests for fuel and collecting firewood, indicating that perhaps the quantity of fuel is important but not necessarily the quality. The 10 most frequently mentioned EEPs fell under the multiple ecosystem components, fauna, regulating services, water, and flora classes.

Naturalness was the most mentioned EEP followed by fauna (general) in the top 25% of EEPs across regions and organizations (Table 4; refer to the Supplementary Material Table 2 for more detailed Tables 4–9, which show the percentage of documents linking specific EEPs, beneficiaries, and EEP-by-beneficiary combinations for regions, organizations, and tidal wetland types). When looking at regions across all of the documents, the Mid-Atlantic EEPs were statistically different than the Pacific Northwest ($p<0.0001$) and the Northern Gulf of Mexico ($p=0.009$). There were no significant differences between the Northern Gulf of Mexico and the Pacific Northwest EEPs ($p=0.577$). The Mid-Atlantic region tended to focus more on the water related EEPs than the other regions. For example, water quality, water quantity, and water quality regulation (nutrients & retention). The Mid-Atlantic also mentioned flora (general) and multiple ecosystem components (general) more while the Pacific Northwest mentioned water movement/navigability more and the Northern Gulf of Mexico mentioned edible fauna more. Collectively, the Mid-Atlantic region documents mentioned top 25% EEPs more often than the other regions; as stated at the beginning of the results, the regions did not differ significantly in length of documents and each region had a similar number of documents analyzed. Table 10 shows that, although the regions addressed almost the same number of EEPs in at least one document, the Mid-Atlantic region focused on them in more documents than the other regions.

When looking at organizations across all of the documents, land steward and state and local agency EEPs were each significantly different than the other organizations ($p<0.0001$), but federal agencies and wetland conservation organizations did not significantly differ ($p=0.839$). Federal agencies mentioned the second highest number of EEPs in at least one document, but they tended to focus on EEPs in the least number of documents. Collectively, land steward documents mentioned top 25% EEPs more than the other organization categories and they also mentioned the highest number of EEPs in at least one document. (The land steward category had more documents with more page numbers to use in the analysis and therefore more opportunities for EEPs to be mentioned).

Across tidal wetland types, naturalness was mentioned the most followed by fauna (general) when comparing the top 25% of EEPs (Table 5). The EEPs of the four tidal wetland classes were statistically different from each other across all of the documents ($p<0.0001$), with tidal wetlands (general) having the highest mean followed by emergent wetlands, forested wetlands, and then scrub-shrub wetlands. This could indicate that wetland managers focused on different benefits for different tidal wetlands types. Tidal wetlands (general) were mentioned in combination with EEPs in more documents; this could be because most documents focused on tidal wetlands (general) as opposed to a specific tidal wetland type because tidal wetlands (general) were also mentioned with the highest number of EEPs in at least one document. For tidal wetlands (general), regulating services (general) and water quality regulation (nutrients and retention) was frequently mentioned.

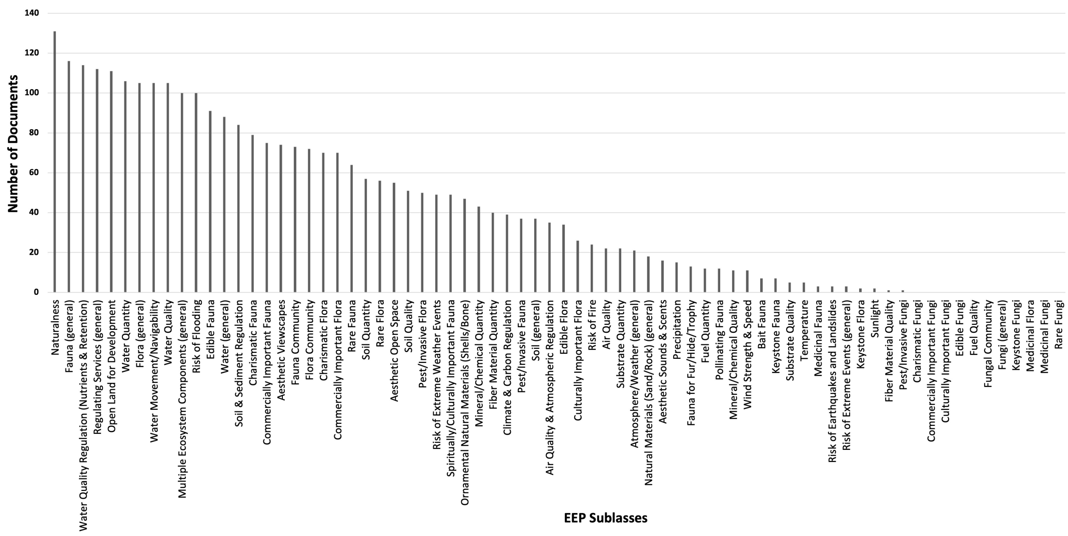


FIGURE 1
Number of documents mentioning each EEP subclass.

TABLE 4 The top 25% of EEPs across regions and organizations.

EEP Class	EEP Subclass	Regions			Organizations			
		Pacific Northwest	Northern Gulf of Mexico	Mid-Atlantic	Federal Agencies	State & Local Agencies	Wetland Conservation Organizations	Land Stewards
Flora	Flora (general)							
	Commercially Important Flora							
Fauna	Fauna (general)							
	Charismatic Fauna							
	Commercially Important Fauna							
	Edible Fauna							
	Fauna Community							
Water	Water (general)							
	Water Quality							
	Water Quantity							
	Water Movement/Navigability							
Multiple Ecosystem Components	Multiple Ecosystem Components (general)							
	Aesthetic Viewscapes							
	Naturalness							
	Open Land for Development							
Regulating Services	Regulating Services (general)							
	Water Quality Regulation (Nutrients & Retention)							
	Soil & Sediment Regulation							
Risk of Extreme Events	Risk of Flooding							

Regions		Organizations	
Percentiles	**Color**	**Percentiles**	**Color**
Less than 25% threshold		Less than 25% threshold	
0–25%		0–25%	
25.1–50%		25.1–50%	
50.1–75%		50.1–75%	
75.1–95%		75.1–95%	
95.1–100%		95.1–100%	

The colors in the cells represent the percentile thresholds for the top 25% of EEPs within regions and organizations independently. For regions, the top 25% was based on the average frequency of each EEP subclass across the three regions. For organizations, the top 25% was based on the average frequency of each EEP subclass across the four organizations. The cells that are unhighlighted represent EEP subclasses that did not meet the top 25% threshold for either the regions or the organizations but did for the other.

TABLE 5 The top 25% of EEPs across tidal wetland types.

EEP Class	EEP Subclass	Tidal Wetlands (general)	Emergent Wetlands (marsh)	Forested Wetlands	Scrub-Shrub Wetlands
Flora	Flora (general)				
	Flora Community				
	Charismatic Flora				
Fauna	Fauna (general)				
	Charismatic Fauna				
	Commercially Important Fauna				
	Edible Fauna				
	Fauna Community				
Water	Water (general)				
	Water Quality				
	Water Quantity				
	Water Movement/Navigability				
Multiple Ecosystem Components	Multiple Ecosystem Components (general)				
	Naturalness				
	Open Land for Development*				
Regulating Services	Regulating Services (general)				
	Water Quality Regulation (Nutrients & Retention)				
Risk of Extreme Events	Risk of Flooding				

Percentiles	Color
0%	
0.01–25%	
25.1–50%	
50.1–75%	
75.1–95%	
95.1–100%	

*In general, for wetlands, an ecosystem service of open land for development may not be practical or allowable.
The colors in the cells represent the percentile thresholds for the top 25% of EEPs within tidal wetland types.

Scrub-shrub wetlands were mentioned the least in combination with EEPs, both in terms of the total number of EEPs mentioned with scrub-shrub wetlands in at least one document and the number of documents mentioning this combination. This could be because scrub-shrub wetlands are often neglected or viewed as wasteland and only 41 of the 141 documents mentioned scrub-shrub wetlands by any keyword at all, those mentioned the most being fauna (general) and naturalness. Forested wetlands tended to focus on fauna community and water quality less than tidal wetlands (general) and emergent wetlands.

3.2 Do beneficiaries differ among region, organization, or tidal wetland type?

All but three beneficiary subclasses were mentioned in at least one document (Figure 2). Those not mentioned were nonuse value (general), pharmaceutical & supplement suppliers (e.g., utilizing tidal wetlands to research, develop, test, etc. medicine, vitamins, drugs, etc.), and private energy generators (or renewable energy sources on private property), which indicates that these were not priority beneficiaries in tidal wetland management. The lack of

TABLE 6 The top 25% of beneficiaries across regions and organizations.

Beneficiary Class	Beneficiary Subclass	Regions			Organizations			
		Pacific Northwest	Northern Gulf of Mexico	Mid-Atlantic	Federal Agencies	State & Local Agencies	Wetland Conservation Organizations	Land Stewards
Agricultural	Agriculture (general)							
Commercial & Industrial	Commercial Food Extractors & Fisheries							
	Commercial/ Industrial Property Owners							
Government, Municipal, Residential	Government, Municipal, Residential (general)							
	Residential Property Owners							
	Public Property Owners							
Commercial/ Military Transportation	Nonspecific Commercial/ Military Transportation							
Recreational	Recreation (general)							
	Experiencers/ Viewers							
Learning	Educators/ Students							
	Researchers							
Nonuse Value	People Who Care (Existence)							
	People Who Care (Option/ Bequest)							

Regions		Organizations	
Percentiles	Color	Percentiles	Color
Less than 25% threshold		Less than 25% threshold	
0–25%		0–25%	
25.1–50%		25.1–50%	
50.1–75%		50.1–75%	
75.1–95%		75.1–95%	
95.1–100%		95.1–100%	

The colors in the cells represent the percentile thresholds for the top 25% of beneficiaries within regions and organizations independently. For regions, the top 25% was based on the average frequency of each beneficiary subclass across the three regions. For organizations, the top 25% was based on the average frequency of each beneficiary subclass across the four organizations. The cells that are unhighlighted represent beneficiary subclasses that did not meet the top 25% threshold for either the regions or the organizations but did for the other.

TABLE 7 The top 25% of beneficiaries across tidal wetland types.

Beneficiary Class	Beneficiary Subclass	Tidal Wetlands (general)	Emergent Wetlands (marsh)	Forested Wetlands	Scrub-Shrub Wetlands
Agricultural	Agriculture (general)				
Commercial & Industrial	Commercial Food Extractors & Fisheries				
Government, Municipal, Residential	Government, Municipal, Residential (general)				
	Residential Property Owners				
Commercial/ Military Transportation	Nonspecific Commercial Transportation				
Recreational	Recreational (general)				
	Experiencers/Viewers				
	Recreational Boaters				
Learning	Educators/Students				
	Researchers				
Nonuse Value	People Who Care (Existence)				
	People Who Care (Option/Bequest)				

Percentiles	Color
0%	
0.01–25%	
25.1–50%	
50.1–75%	
75.1–95%	
95.1–100%	

The colors in the cells represent the percentile thresholds for the top 25% of EEPs within tidal wetland types.

documents mentioning general nonuse values could be because organizations were more specific when discussing beneficiaries. For example, instead of saying “nonuse resources” a document might say “enhance, protect, and maintain salt marshes” in reference to people who care about salt marshes from an existence standpoint. The 10 most frequently mentioned beneficiaries spanned a wide variety of classes, including nonuse value, government/municipal/ residential, learning, recreation, agriculture, and commercial/ military transportation.

People who care (existence) was the most mentioned beneficiary followed by government, municipal, residential (general), researchers, and experiencers/viewers in the top 25% of beneficiaries across regions and organizations (Table 6). When looking at regions across all of the documents, the Mid-Atlantic beneficiaries were statistically different than the Pacific Northwest ($p<0.0001$) and the Northern Gulf of Mexico ($p=0.008$), as was the case for EEPs. There were no significant differences between the Northern Gulf of Mexico and the Pacific Northwest beneficiaries ($p=0.148$). Documents from the Northern Gulf of Mexico did not mention agriculture (general) as much as the Mid-Atlantic and the Pacific Northwest regions. Documents from the Northern Gulf of Mexico mentioned commercial food extractors and fisheries more than the Mid-Atlantic and the Pacific Northwest. However, all three regions have very active fishing and seafood harvest industries. Similar to the top 25% of EEPs, the Mid-Atlantic region collectively mentioned top 25% beneficiaries more often than the other regions. Even though the regions addressed almost the same number of beneficiaries in at least one document (Table 11), the Mid-Atlantic region mentioned them in more documents than the other regions.

When looking at organizations across all of the documents, there were similarities to the EEPs because the land steward and state and local agency beneficiaries were each significantly different than the other organizations ($p<0.0001$), but federal agencies and wetland conservation organizations did not significantly differ ($p=0.973$). Both federal agencies and wetland conservation organizations mentioned commercial/industrial property owners, residential property owners, and nonspecific commercial/military transportation less than the other organizations indicating that

TABLE 8 Top 50% of EEP-by-beneficiary subclass combinations for all documents.

EEP Subclass/ Beneficiary Subclass	People Who Care (Existence)	Government, Municipal, Residential (general)	Researchers	People Who Care (Option/Bequest)	Experiencers/Viewers	Educators/Students	Residential Property Owners	Recreation (general)	Commercial/Industrial Property Owners	Agriculture (general)	Nonspecific Commercial/Military Transportation	Commercial Food Extractors Fisheries	Learning (general)	Recreational Boaters	Public Property Owners	Farmers	Recreational Fishermen	Nonspecific Inspirational	Transporters of People	Recreational Hunters	Humanity & Public Health	Commercial & Industrial (general)	Military & Coast Guard
Naturalness																							
Fauna (general)																							
Regulating Services (general)																							
Open Land for Development																							
Water Movement/Navigability																							
Risk of Flooding																							
Water Quality Regulation (Nutrients & Retention)																							
Flora (general)																							
Water Quantity																							
Multiple Ecosystem Components (general)																							
Edible Fauna																							
Water Quality																							
Water (general)																							
Charismatic Fauna																							
Commercially Important Fauna																							
Aesthetic Open Space																							
Fauna Community																							
Flora Community																							
Aesthetic Viewscapes																							
Soil & Sediment Regulation																							
Charismatic Flora																							
Commercially Important Flora																							

(Continued)

TABLE 8 Continued

EEP Subclass/ Beneficiary Subclass	People Who Care (Existence)	Government, Municipal, Residential (general)	Researchers	People Who Care (Option/Bequest)	Experiencers/Viewers	Educators/Students	Residential Property Owners	Recreation (general)	Commercial/Industrial Property Owners	Agriculture (general)	Nonspecific Commercial/Military Transportation	Commercial Food Extractors Fisheries	Learning (general)	Recreational Boaters	Public Property Owners	Farmers	Recreational Fishermen	Nonspecific Inspirational	Transporters of People	Recreational Hunters	Humanity & Public Health	Commercial & Industrial (general)	Military & Coast Guard
Rare Fauna	95.1–100%	75.1–95%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Risk of Extreme Weather Events	75.1–95%	75.1–95%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Soil Quality	75.1–95%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Soil Quantity	75.1–95%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Spiritually/Culturally Important Fauna	75.1–95%	75.1–95%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Pest/Invasive Flora	75.1–95%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Pest/Invasive Fauna	75.1–95%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%
Mineral/ Chemical Quantity	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%
Climate & Carbon Regulation	75.1–95%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	0%
Soil (general)	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	0%	50.1–75%	50.1–75%	0%	0%	50.1–75%
Air Quality & Atmospheric Regulation	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%
Culturally Important Flora	75.1–95%	50.1–75%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	0%	50.1–75%	0%	0%	0%
Natural Materials (Sand/ Rock) (general)	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	0%	0%	50.1–75%	0%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%	50.1–75%
Ornamental Natural Materials (Shells/Bone)	75.1–95%	50.1–75%	50.1–75%	50.1–75%	75.1–95%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	50.1–75%	0%	50.1–75%

Percentiles	Color
0%	
0.01–25%	
25.1–50%	
50.1–75%	
75.1–95%	
95.1–100%	

The colors in the cells represent the percentage of documents that the EEP-by-beneficiary combination showed up in. The percentiles are based on all of the documents.

benefits related to property and transportation might be less of a priority for managers in these organizations. Land stewards mentioned commercial food extractors & fisheries, educators/students, and people who care (option/bequest) more than the other organizations. Federal agencies did not mention educators/students as much as the other organizations. This may suggest that local organizations focus on education and outreach programs in their wetland management publications more than other types of organizations. Collectively, land steward documents mentioned beneficiaries in total more often than other organizations and they also mentioned slightly more beneficiaries in at least one document than the other organizations. But, there were more land steward documents and pages used in this analysis, so there was more opportunity for beneficiaries to be mentioned.

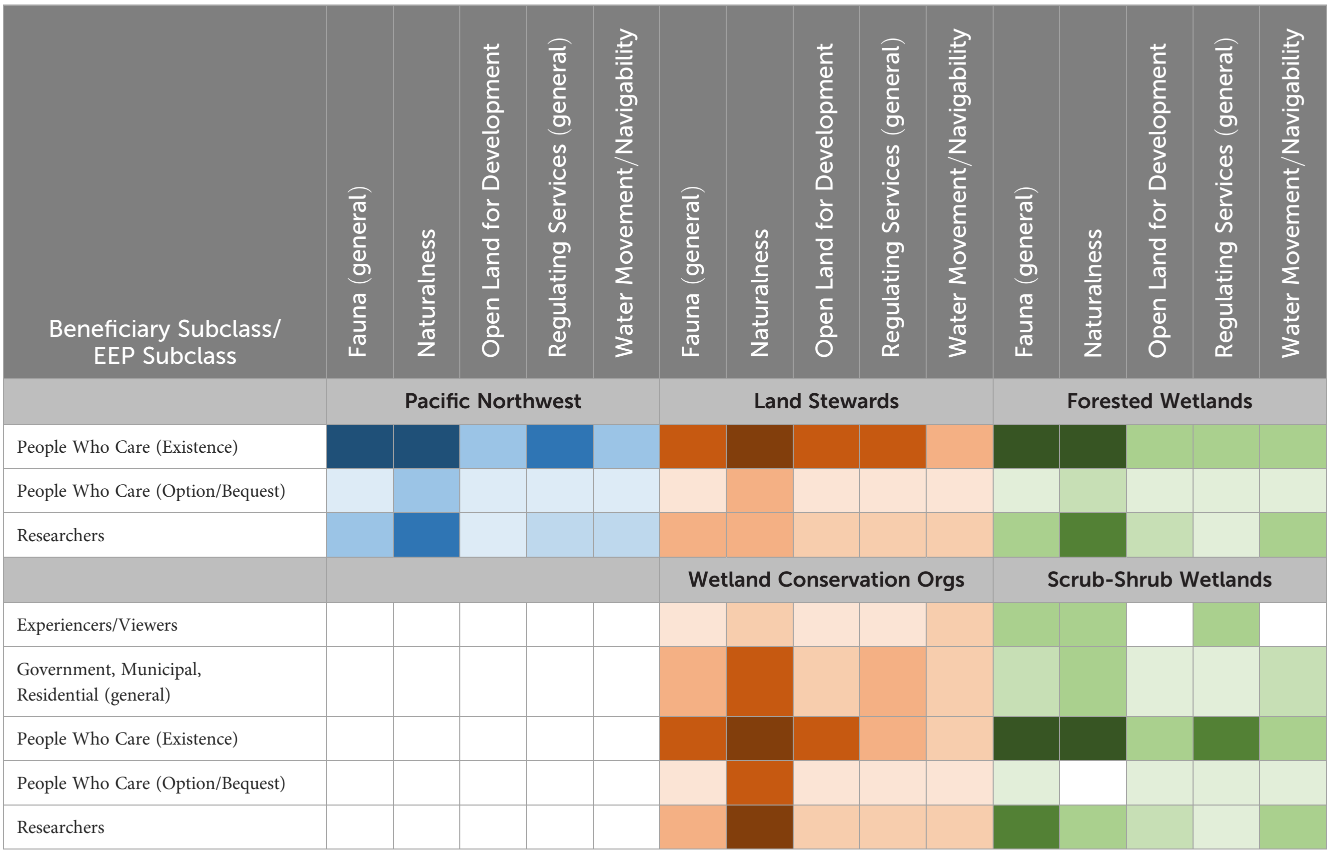
Across tidal wetland types, people who care (existence), government, municipal, residential (general), and researchers were mentioned the most when comparing the top 25% of beneficiaries (Table 7). The beneficiaries of the four tidal wetland classes were statistically different from each other across all of the documents (p<0.0001), which lines up with the region and organization results. Tidal wetlands (general) had a higher mean than the others and almost twice as high as emergent wetlands. Recreational boaters were mentioned more for tidal wetlands (general) than the other wetland types and scrub-shrub wetlands was the only wetland type to not mention nonspecific commercial transportation. Similar to the top 25% of EEPs, tidal wetlands (general) were mentioned more with beneficiaries, but this could be because most of the documents focused on tidal wetlands (general) as opposed to a specific tidal wetland type because tidal wetlands (general) were also mentioned with the highest number of beneficiaries in at least one document, although only slightly higher than emergent wetlands. Scrub-shrub wetlands were mentioned the least when it came to beneficiaries, both in terms of number of documents mentioning a scrub-shrub and beneficiary combination, and in terms of the total number of beneficiaries mentioned with scrub-shrubs in at least one document.

TABLE 9 Comparison of top 5 EEP-by-beneficiary subclass combinations across regions, organizations, and tidal wetland types.

Beneficiary Subclass/ EEP Subclass	Fauna (general)	Naturalness	Open Land for Development	Regulating Services (general)	Water Movement/Navigability	Fauna (general)	Naturalness	Open Land for Development	Regulating Services (general)	Water Movement/Navigability	Fauna (general)	Naturalness	Open Land for Development	Regulating Services (general)	Water Movement/Navigability
	Mid-Atlantic					Federal Agencies					Tidal Wetlands (general)				
Experiencers/Viewers															
Government, Municipal, Residential (general)															
People Who Care (Existence)															
People Who Care (Option/Bequest)															
Researchers															
	Gulf of Mexico					State and Local Agencies					Emergent Wetlands				
Experiencers/Viewers															
Government, Municipal, Residential (general)															
People Who Care (Existence)															
People Who Care (Option/Bequest)															
Researchers															
	Pacific Northwest					Land Stewards					Forested Wetlands				
Experiencers/Viewers															
Government, Municipal, Residential (general)															

(Continued)

TABLE 9 Continued



Regions		Organizations		Tidal Wetland Types	
Percentiles	Color	Percentiles	Color	Percentiles	Color
0%		0%		0%	
0.1–25%		0.1–25%		0.1–25%	
25.1–50%		25.1–50%		25.1–50%	
50.1–75%		50.1–75%		50.1–75%	
75.1–95%		75.1–95%		75.1–95%	
95.1–100%		95.1–100%		95.1–100%	

The colors in the cells represent the percentile thresholds for the top 5 combinations (based on the number of documents a particular combination was mentioned in) within regions, organizations, and tidal wetland types independently.

3.3 Does the use of EEPs by beneficiaries differ among region, organization, or tidal wetland type?

Across all 141 documents, the EEP-by-beneficiary subclass combination most mentioned was naturalness paired with people who care (existence) which showed up in 86% of the documents (Table 8). For example, a document might mention "restoring and protecting rare and endangered species and habitat" because people care about the existence of all species and the prevention of any from going extinct. Naturalness was mentioned with most of the beneficiaries, and people who care benefited from the existence of most of the EEPs. Government, municipal, residential (general) along with researchers were beneficiaries of many of the EEPs and fauna (general) and regulating services (general) were important to most beneficiaries.

When looking at the EEP-by-beneficiary combinations across all documents for regions, all were statistically different from each other ($p=0.033$). The model did not converge when EEP-by-beneficiary combinations included fungi because the counts were so low, so any combination including fungi was excluded from statistical analyses. The statistical results were interesting because on their own, the Northern Gulf of Mexico and Pacific Northwest EEPs and beneficiaries were not statistically different from each other. Perhaps when making it explicit which beneficiary was being considered for which EEP, differences emerged. For example, in the Pacific Northwest, fauna (general) was a frequently found pair for people who care (existence) (e.g., "restore important habitat for

TABLE 10 Out of 72 total EEPs, this table provides the number of EEPs mentioned in at least one document for each region, organization, and tidal wetland type.

Categories	Pacific Northwest	Northern Gulf of Mexico	Mid-Atlantic	Federal Agencies	State and Local Agencies	Wetland Conservation Organizations	Land Stewards	Tidal Wetlands (general)	Emergent Wetlands (marsh)	Forested Wetlands	Scrub-Shrub Wetlands
Number of EEPs	58	57	58	53	49	48	59	60	57	49	38

TABLE 11 Out of 46 total beneficiaries, this table provides the number of beneficiaries mentioned in at least one document for each region, organization, and tidal wetland type.

Categories	Pacific Northwest	Northern Gulf of Mexico	Mid-Atlantic	Federal Agencies	State and Local Agencies	Wetland Conservation Organizations	Land Stewards	Tidal Wetlands (general)	Emergent Wetlands (marsh)	Forested Wetlands	Scrub-Shrub Wetlands
Number of beneficiaries	43	42	42	40	40	40	43	43	42	37	22

fish") and more so than the other regions, which focused on naturalness for people who care (option/bequest) more so than the Pacific Northwest (Table 9). An example of the combination naturalness and people who care (option/bequest) would be "protecting the native habitat and its species from future development" which focuses on the option of future generations to benefit from the natural habitat and species. Naturalness paired with people who care (existence) and government, municipal, residential (general) were top combinations across all three regions. An example of the combination naturalness paired with government, municipal, residential (general) would be "restore a key tidal wetland near the center of the city" which addresses natural wetland habitat in the city center without identifying a beneficiary more specific than the city as a whole. All three regions also frequently mentioned naturalness with researchers (e.g., "researchers monitor the ecological outcomes of restoration efforts") and regulating services (general) with people who care (existence). An example of this combination would be "build resiliency against the effects of climate change and sea level rise" which addresses protecting a coastline against climate change without identifying a beneficiary more specific than people who care about coastal communities.

When looking at the EEP-by-beneficiary combinations across all of the documents for organizations, all were statistically different from each other ($p<0.0001$). These statistical results were also interesting because on their own, the federal agency and wetland conservation organization EEPs and beneficiaries were not statistically different from each other. Same with regions, this could be because differences emerged when making it explicit which beneficiary was being considered for which EEP. Open land for development, paired with people who care (existence) (e.g., "saving an area of land for potential future development"), was a top combination for land stewards and wetland conservation organizations more so than the other organizations. State and local agencies were the only organization that did not have fauna (general) for people who care (existence) as a top combination and wetland conservation organizations were the only organization to not have regulating services (general) for people who care (existence) as a top combination. As with the regions, naturalness paired with people who care (existence) was a top combination across all four organizations. For state and local agencies and land stewards, naturalness was also a top combination with government, municipal, residential (general). Federal agencies and wetland conservation organizations both frequently mentioned naturalness with researchers, which makes sense as many federal agencies and wetland conservation organizations focus on environmental-based research. For federal agencies, state and local agencies, and land stewards, regulating services (general) was frequently mentioned for people who care (existence). Overall, organizations might have differed in what EEP was important to each beneficiary but had similar top EEPs; so, entities can have similar priority EEPs, but the people using those EEPs may be different.

The EEP-by-beneficiary combinations were statistically different among all tidal wetland types across all of the documents ($p<0.0001$). These results were similar to the statistical results for EEPs and beneficiaries individually. Naturalness was a

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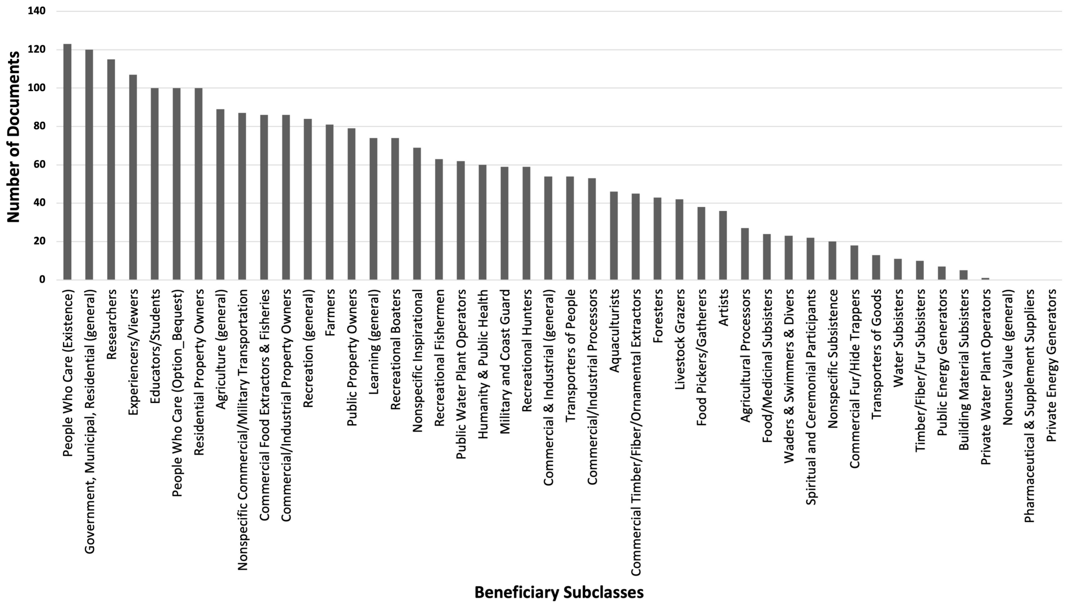

FIGURE 2
Number of documents mentioning each beneficiary subclass.

top EEP for people who care (existence) for all four tidal wetland types. Naturalness was also frequently mentioned with researchers for all tidal wetland types except scrub-shrub wetlands, showing that naturalness is of interest to those studying certain tidal wetlands. Similarly, scrub-shrub wetlands were the only type to not have naturalness frequently mentioned with the beneficiary government, municipal, residential (general), which could be because, as a whole, governments, municipalities, and residential areas care about the natural tidal wetlands in their communities. People who care (existence) was frequently mentioned with fauna (general) along with regulating services (general); so, in general, these management organizations think that people who care focus on the fauna in tidal wetlands and the ability for the tidal wetland to regulate water, air, etc. A more detailed look at the top 10 combinations of EEP-by-beneficiary subclass combinations across regions, organizations, and tidal wetland types is provided in the Supplementary Material.

4 Discussion

When looking at the trends in the priority EEPs across regions, organizations, and tidal wetland types, the documents frequently mentioned many of the same EEPs, indicating shared interests among wetland restoration managers in the different regions and organizations with regard to the tidal wetland types. The Pacific Northwest and the Northern Gulf of Mexico regions were more similar in EEP priorities than the Mid-Atlantic. Federal agencies and wetland conservation organizations each were more similar in EEP priorities than state and local agencies and land stewards. Each of the four tidal wetland types differed from the other three in EEP priorities. Naturalness was the top priority overall with fungi being the least prioritized. Fauna (general) and water quality regulation were also a top priority overall.

Priority beneficiary patterns across regions, organizations, and tidal wetland types showed that documents also frequently mentioned many of the same beneficiaries, indicating shared beneficiary interests among wetland restoration managers. Like priority EEPs, the Pacific Northwest and the Northern Gulf of Mexico documents were more similar in beneficiary priorities than documents from the Mid-Atlantic. Regarding beneficiaries, as with EEPs, federal agencies and wetland conservation organizations each were more similar in beneficiary priorities than state and local agencies and land stewards. Each of the four tidal wetland types differed from the other three in beneficiary priorities. People who care (existence) were the top priority overall and nonuse value (general), pharmaceutical and supplement suppliers, and private energy generators were the lowest priority.

Significant differences among regions suggests that priorities for EEPs and beneficiaries are not the same everywhere within the US. Likewise, differences among organizations in rankings of EEPs and beneficiaries suggests that there may be institutional differences associated with the entities responsible for managing a given tidal wetland. Thus, restoration practitioners should be mindful of these differences in priorities when either working with other wetland stakeholders to develop a restoration plan, or when using the literature to identify priority ecosystem services, EEPs, or beneficiaries. On the positive side, the considerable overlap in which EEPs or beneficiaries were included in the top 25% for each region or organization might suggest that wetland restoration practitioners could choose to start from the "long list" of EEPs or beneficiaries (i.e., Tables 4–7) when working with stakeholders to develop goals and plans.

It is important to acknowledge that ecosystem services include more than just the easily measurable, valued, or useable goods and

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services such as water quantity. People benefit from nature by simply knowing it exists, so NESCS Plus uses the 'people who care' beneficiary subclasses to capture this benefit. Both naturalness and people who care were strongly linked and frequently prioritized across regions, organizations, and tidal wetland types. These results show that wetland restoration managers believe that people who care are important beneficiaries, and the existence of nature is an important benefit to consider when designing restoration projects.

Livestock grazers were a top beneficiary in Pacific Northwest documents. The Pacific Northwest has much farmland in coastal watersheds (Horst, 2019), and coastal tidal wetlands of the Pacific Northwest have been used for farming, particularly cattle grazing, for over a century. Presently, many coastal communities are restoring wetlands that had been converted to farming. For example, Tillamook, Oregon suffers from flooding in winter exacerbated by diking and farming of former wetlands, and the community is currently restoring wetlands to reduce flooding and improve other ecosystem services (Hernandez et al., 2022). Dairy pastures are likewise being restored to wetlands on the Columbia River estuary for juvenile salmon habitat (Littles et al., 2022). Comparatively, there is less livestock grazing in coastal Northern Gulf of Mexico or the Mid-Atlantic regions (Karl et al., 2009), which could explain why livestock grazers did not show up as a top EEP for those two regions.

One limitation of this document analysis approach was the difference in number of pages among documents. To help alleviate this, a presence/absence approach was used to identify and classify an ecosystem services triplet, that is, if a document mentioned an ecosystem services triplet at all, it was assumed to be important to the organization. Another limitation of this approach was the difference in number of documents among management organization categories. For example, there were 56 documents in the land steward category but only 20 each in the federal agency and wetland conservation organization categories. To help alleviate this, the percentage of ecosystem services triplet counts was based on the number of documents in each category as opposed to the total number of documents. Still, the land steward category mentioned ecosystem services more than the other organizations and given that there was sufficient evidence to say that document lengths were different among organizations, the fact that there were more land steward documents could have been a contributing factor. Among regions, the Mid-Atlantic region mentioned about the same number of total EEPs and beneficiaries in at least one document as the other regions, but they mentioned ecosystem services as a whole in more documents than the other regions. There was not sufficient evidence to say that the regions differed in document length, so tidal wetland managers in the Mid-Atlantic region could just be more focused on ecosystem services than in the Northern Gulf of Mexico or Pacific Northwest.

Recent work has shown ecosystem services to be critical to restoration efforts, but infrequently reported by wetland restoration monitoring programs. Ecosystem services can help inform goal setting, project alternative evaluation (Daoust et al., 2014), monitoring and metrics development (Jackson et al., 2022), and engagement with stakeholders and the public (Hernandez et al., 2022). There are many tools available that can help incorporate ecosystem services into restoration (Jackson et al., 2022), many of them that work well with the approach used for this project (i.e., the FEGS Scoping Tool and NESCS Plus). This approach may also be used to complement other approaches for identifying priority ecosystem services. For example, the results from this project complement a more bottom-up approach using the FEGS Scoping Tool in a Tillamook River Wetlands project (Hernandez et al., 2022). In that project, EPA scientists worked with restoration managers on a wetland restoration project along the Tillamook River to prioritize stakeholders, beneficiaries, and environmental attributes of the project. The results from the Tillamook River Wetlands analysis, plus results from this literature-based analysis, can both be used to inform planning for project goals, metrics, and monitoring of the Tillamook River Wetlands restoration project. As stated in the methods, we recognize that the restoration documents reviewed were inconsistent in specifying whether community input was used when developing each restoration plan. Even when direct beneficiary and/or stakeholder outreach is done and welcomed by managers (Pindilli et al., 2018), it is still time consuming and can be difficult to accomplish. Another approach, therefore, is to ask stakeholders and managers to identify and prioritize ecosystem services (Sharpe et al., 2020). The type of document analysis approach used in this paper is the most feasible approach for digesting a large number of documents to draw big-picture conclusions and find cross-region, -organization, and -habitat comparisons. However, if possible, input from local communities and those impacted by a wetland restoration project would be a useful comparison to see how manager priorities compare to beneficiary priorities.

The type of approach used in this paper is well-suited for many circumstances. For example, it can: 1) provide managers with insight before engaging stakeholders; 2) inform managers which stakeholders need to be included (e.g., people who care) and why; 3) help check the results of a stakeholder-driven prioritization for consistency with other restoration goals within a region or tidal wetland type; and 4) provide an opportunity for stakeholders to have priorities presented in understandable language and be able to react/respond to them. Organizations might use this approach to assess whether their restoration or management goals consider the interests of all relevant beneficiaries, and in particular agencies might use it to identify whether management efforts by other organizations will contribute to regional goals, and to identify potential areas of conflict. For example, Yee et al. (2023) utilized this approach in the Massachusetts Bays National Estuary Partnership (MassBays) planning area and identified additional ecosystem services to be included in MassBays' restoration targets for coastal habitats. This approach was also used in Rossi et al. (2022) to analyze documents for potentially relevant ecosystem services, beneficiaries, and local priorities.

5 Conclusion

This analysis provided relevant and prioritized lists of ecosystem services that can be used to inform restoration goal setting and development of monitoring metrics. Strong, yet unexpected commonalities were identified. For example, the EEP naturalness paired with the beneficiary people who care (existence) was a top combination across all three regions, all four organizations, and all four tidal wetland types, and naturalness was a main topic among researchers. The EEPs most frequently mentioned were naturalness and fauna (general).

Certain EEPs can be a top priority for a region or community, such as water quality regulation, but the way an EEP is used changes depending on the specific beneficiary. For example, if the goal of a restoration project is to improve water quality regulation, the regulations would need to be stricter for water being used by waders, swimmers, and divers compared to regulations for areas where people just enjoy the experience/view of the water. This was showcased with organizations where naturalness was a top EEP that was frequently mentioned with researchers for federal agencies and wetland conservation organizations, with residential property owners for state and local agencies, and with experiencer/viewers for land stewards. Each of these beneficiaries would care about naturalness in a different way so restoration and monitoring aims and methods could look different depending on which beneficiaries were of focus. Pinpointing exactly who will benefit from an EEP will help make metrics and the measurement of success more accurate and relevant. This can be important for ensuring restoration efforts are responsive to a full suite of stakeholders and help ensure that communities with different socio-economic backgrounds or interests are not overlooked in capturing priorities for a restoration project. The list of stakeholders for a given decision context may be lengthy but stakeholders need to be carefully considered; in our tidal wetland example, the beneficiaries most frequently mentioned were people who care (existence), government, municipal, residential (general), researchers, and experiencers/viewers.

Those not mentioned, and therefore likely not a known or recognized priority of wetland restoration managers, included the fungi EEP and the pharmaceutical & supplement suppliers and private energy generators beneficiaries. Overall, the Mid-Atlantic region and the land steward organizations mentioned ecosystem services more than the other regions and organizations, and tidal wetlands (general) were mentioned in combination with EEPs and beneficiaries more than the other more specific tidal wetland types.

These methods are transferable to other types of ecosystems, locations, and environmental management problems where there is a need to link site ecological condition to the production of ecosystem services. The power of this approach is that the ecosystem services were prioritized based on the interests described by organizations within these regions that are charged with stewarding and restoring wetlands and informed by their stakeholders. Such lists can be used in future restoration projects to inform: 1) goal setting by identifying socially relevant restoration goals; 2) metrics identification and development based on these goals; and 3) stakeholder engagement and communication with restoration practitioners.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CJ: Writing – original draft, Writing – review & editing. CH: Writing – review & editing. SY: Writing – review & editing. MN: Writing – review & editing. HD: Writing – review & editing. AB: Writing – review & editing. MH: Writing – review & editing. TD: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2024.1260447/full#supplementary-material

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