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Integrating ecosystem technology into coastal and marine infrastructure: biodiversity assessments and methodologies for comparative analyses

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The integration of “greening the gray” (GTG) into marine infrastructure represents a transformative approach to enhancing biodiversity and ecosystem services in heavily modified environments. However, the ecological effectiveness of GTG remains hindered by inconsistent methodologies and knowledge gaps. This study proposes a methodological approach for GTG biodiversity assessments, focusing on appropriate control site selection, integration of count and coverage data through occupancy methods, and applying coverage-based rarefaction to address sampling biases. The approach facilitated consistent evaluation of biodiversity data and reliable evaluation of GTG performance across various contexts, specifically using a GTG project at the Port of Vigo in Spain as a case study. This methodology structure supports sustainable marine infrastructure development by providing scalable, evidence-based methodologies for biodiversity assessment and fostering international collaboration among ecologists, developers, and stakeholders.

KEYWORDS

ecosystem technology (EcoTech), nature inclusive design (NID), ecosystem services, greening the grey, standardized monitoring

1 Introduction

Ecosystem Technology (Ecotech) focuses on developing and implementing environmentally friendly, resource-efficient technologies and is supportive of long-term ecological health (Straškraba, 1993; Moser, 1994; Haddaway et al., 2018). These include emerging proactive strategies such as ecomimicry and engineering with nature (Firth et al., 2016a,b), which aim to mitigate environmental impacts by applying different technological solutions to enhance biodiversity and ecosystem services (Straškraba, 1993; Moser, 1994; Naylor et al., 2017; Firth et al., 2020, 2024). Integrating these “greening the gray” (GTG) technologies within built environments, such as coastal and marine infrastructure, represents a holistic approach that addresses ecosystem and operational services in parallel to essential engineering functions. However, the efficacy and long-term sustainability of GTG EcoTech remain subject to ongoing research (Firth et al., 2024).

As urbanization and climate change continue to drive the replacement of natural habitats with artificial structures, the need for GTG EcoTech becomes increasingly urgent. The global expansion of marine construction, driven by climate change and urbanization, has transformed coastlines into heavily modified environments (Gittman et al., 2015; Gittman et al., 2016; Firth et al., 2016a,b; Floerl et al., 2021). These anthropogenic changes, which include seawalls,

breakwaters, and artificial islands, create “novel ecosystems” with complex ecological consequences. Marine infrastructure is not inherently designed with nature in mind; however, it can utilize GTG EcoTech, such as ecomimicry, to enhance ecosystem services (Marshall and Lozeva, 2009; Perkol-Finkel and Sella, 2015; Sella et al., 2022). The successful use of ecomimicry depends on an understanding of place-based ecosystem processes that can be used to balance and sustain the ecosystem in context (Straškraba, 1993; Winter et al., 2020).

Despite the potential benefits, significant knowledge gaps persist regarding the ecological performance and assessments of infrastructure that apply GTG EcoTech. This necessitates moving beyond conceptual application and towards evidence-based assessments of how these technologies can support and enhance a site's ecology. Biodiversity, for example, is increasingly recognized for its intrinsic value and role in providing ecosystem services and promoting ecosystem health (Laurila-Pant et al., 2015; Batavia and Nelson, 2017). The United Nations has established policy objectives for marine resources through its 14th Sustainable Development Goal (United Nations General Assembly, 2015). To achieve ‘sustainable development,’ stakeholders must be able to determine what success looks like. As such, there is a growing need to accurately assess and compare biological diversity, as existing environmental frameworks may not adequately address this in marine infrastructures (Riisager-Simonsen et al., 2022). This underscores the importance of integrating assessment protocols into regulatory frameworks.

Achieving uniform biodiversity assessment methodologies where GTG EcoTech is utilized is essential for several reasons. First, marine infrastructure varies in terms of size, location, and configuration (e.g., seawalls, breakwaters, piers, and offshore platforms). Creating a biodiversity assessment framework will allow consistent data to be collected from these different types of structures. Second, it can facilitate data comparisons across sites with varying sampling efforts and methodologies, as well as mitigate data offsetting due to seasonal and geographical differences. A consistent protocol will allow us to determine whether differences in biodiversity are due to the GTG EcoTech implementation, environmental changes, or simply discrepancies in how data was collected or analyzed. Finally, as human activities increasingly alter natural habitats, understanding the efficiency of GTG EcoTech in marine infrastructure is paramount for avoiding “greenwashing” by ineffective strategies (Firth et al., 2020). Consequently, these misleading or deceptive greenwashing claims can promote ineffective strategies that fail to support biodiversity needs or ecological function (Firth et al., 2020).

Despite the diversity of existing frameworks and methods, the absence of a common methodological approach limits comparability across projects and ecosystems. Establishing shared methodologies would allow researchers and practitioners to generate more consistent data, facilitate meta-analyses, and strengthen the evidence base for nature-inclusive infrastructure. From a management and policy perspective, common approaches also provide clarity for decision-makers, reduce the risk of greenwashing, and support transparent evaluation of ecological and social outcomes.

The following paper highlights the importance of developing comparable biodiversity data collection and analysis methodologies, which are crucial for evaluating the effectiveness of different GTG EcoTech interventions. This will allow the quantification and comparison of GTG projects of various forms and locations, thus creating baseline development guidelines. We aim to propose a

methodological approach framework that comprehensively represents biodiversity within the GTG EcoTech study area. This will provide insights into how effective various GTG EcoTech solutions are in increasing biodiversity and other ecosystem services.

2 Challenges and solutions in ecological assessments

Marine infrastructure creates unique ecosystems distinct from natural habitats, necessitating innovative approaches to accurately assess biodiversity and ecosystem dynamics (Ferrario et al., 2016; Knights et al., 2024). Standardized sampling and analysis methodologies are essential for establishing clear criteria for comparing biodiversity across sites sampled under varying conditions (Christie et al., 2019). When formulating the sampling structure, the following elements are necessary for comparability estimates: appropriate controls, unified data from different sampling methods, and standardized sampling effort through data analysis (Figure 1). To showcase these concerns, we have utilized data from the Port of Vigo, Spain (www.livingports.eu, Horizon 2020, GA 970972), where concrete seawalls incorporating EcoTech were placed adjacent to standard concrete seawalls to evaluate differences in biodiversity patterns.

2.1 Case study

The Port of Vigo case study consists of sampling from two distinct nature-inclusive seawall types, ‘Mangrove’ (210m²) and ‘Azuri’ (120m²), and their respective control walls. The seawalls are 11.5 meters apart, made from standard smooth Portland cement. Before construction began, a baseline survey was conducted to assess the existing sessile communities. This survey was performed one month before the construction of the seawalls. Post-installation monitoring was carried out at 3, 6, 9, and 12 months post-deployment on the treatment and control seawalls.

The monitoring array included a total of 40 treatment/control quadrates: 10 for the Mangrove Seawall (5 at intertidal, 5 at subtidal), 10 for the Azuri Seawall (5 at intertidal, 5 at subtidal), 10 for the Mangrove control (5 at intertidal, 5 at subtidal), and 10 for the Azuri control (5 at intertidal, 5 at subtidal). The biological community monitoring of the seawall panels was conducted by photographically documenting randomly placed 30 × 30 cm quadrates. Data collection followed the protocol of Perkol-Finkel et al. (2008), which assesses the percent cover of colonial/encrusting species and the count of solitary organisms. All organisms seen were included in the database; none were excluded.

2.2 Appropriate controls

Evaluating the effectiveness of a GTG treatment requires appropriate controls, which are crucial in ecological experimental research, serving as benchmarks against which the outcomes of interventions can be measured. Research indicates that most studies—approximately 74%—utilize reference or control sites for comparison, although not all do (Wortley et al., 2013; Christie et al., 2019). Controls help isolate the independent variable's effect, ensuring that observed

CHALLENGES IN ECOLOGICAL ASSESSMENTS OF MARINE ECOTECH

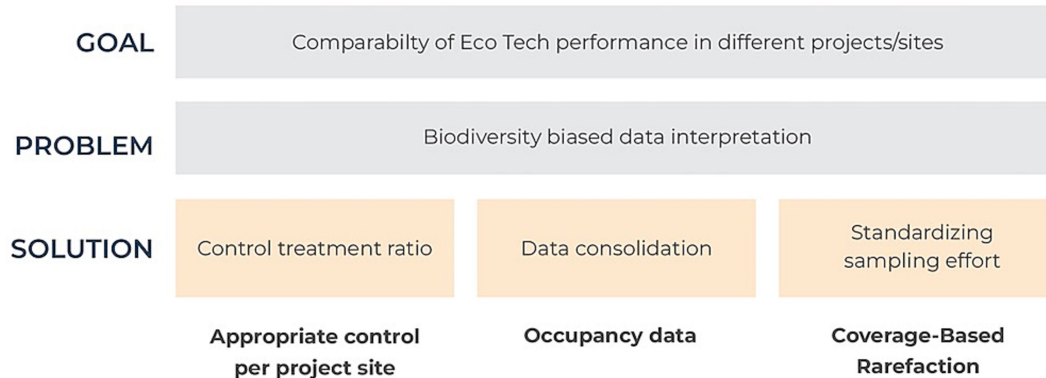


FIGURE 1
Challenges and solutions in ecological assessment of EcoTech applied to marine greening-the-gray infrastructure.

differences are attributable to the treatment rather than confounding factors. For instance, a habitat restoration project may appear successful in increasing marine invertebrate populations; however, without a control site, it is difficult to determine whether this increase is a result of the restoration efforts or merely natural fluctuations in the ecosystem (Osenberg et al., 2006; Suding, 2011; Wortley et al., 2013; Christie et al., 2019).

When selecting a control site for the application of GTG EcoTech in marine infrastructure, it is essential to consider factors such as geographic proximity, habitat similarity, physical conditions (substrate orientation, light availability, oxygen levels, water movement, salinity, and turbidity), and anthropogenic pressures (marine traffic, floating debris, run-offs, etc.). The control site and the GTG EcoTech impacted site should be as similar in attributes as possible, to enable tracking of temporal changes and response to environmental shifts. For example, if the GTG EcoTech infrastructure is a seawall, the control should be an adjacent standard seawall under similar environmental conditions and anthropogenic pressures that can accommodate the same survey method and effort. Marine infrastructure can significantly differ from the natural environment. For instance, the efficiency of GTG EcoTech on a vertical seawall constructed on a sandy bottom should be assessed relative to a standard seawall in the same setting, rather than comparing it directly to the sandy bottom habitat itself.

As such, we recommend utilizing the Randomized Control-Impact (R-CI) methodology, which evaluates the ecological effects of an intervention by randomly assigning treatment sites (i.e., the GTG infrastructure) and control sites (status quo infrastructure), allowing researchers to compare outcomes and isolate the impact of the intervention. This minimizes the need for pre-intervention sampling and is a reliable method for understanding the effect of manipulating a variable in an ecosystem (Carpenter et al., 1989). This approach distributes confounding factors (e.g., environmental variability) equally across treatment and control groups, which ensures comparability and reduces initial differences between groups,

provided sufficient sites and temporal sampling points are included (De Palma et al., 2018; Larsen et al., 2019; Christie et al., 2020). Without appropriate controls, studies risk misleading conclusions and the continuation of ineffective practices, ultimately hindering the advancement of ecological science.

2.3 Combining count and cover data

The methodology for data capture should comprehensively represent the study area's biodiversity and maximize data consolidation. Two major methods of biodiversity assessment are coverage percentage for colonial or sprawling species and count data for solitary species (Murray, 2001). This forced segmentation of biodiversity data into "count" species and "cover" species complicates meaningful comparisons at the community level (Figures 2A,B). There are statistical methods to move from cover data to count data, but these typically require additional information, such as the size or mass of the recorded species, that is not always available (Zvuloni and Belmaker, 2016).

The categorization of species data into "count" versus "cover" introduces bias because each metric captures distinct aspects of a species' presence and influence within an ecosystem. Count data emphasizes numerical abundance, possibly overstating the ecological importance of small, numerous organisms and underrepresenting the impact of large, sparse ones (Elphick, 2008). Count data is also highly sensitive to sampling methodology (Elphick, 2008). Conversely, cover data reflects spatial dominance, which can underemphasize the contribution of small but abundant species and overemphasize larger, less abundant species, ultimately providing a limited view of population structure and dynamics (Miller and Ambrose, 2000). One solution for this issue is the consolidation of data by calculating occupancy for both types of species. For example, when assessing the species composition of a quadrat or transect, the sampling unit should be divided into many smaller units (cells). Then, instead of an overall estimate of the number (for solitary organisms) or cover (for colonial

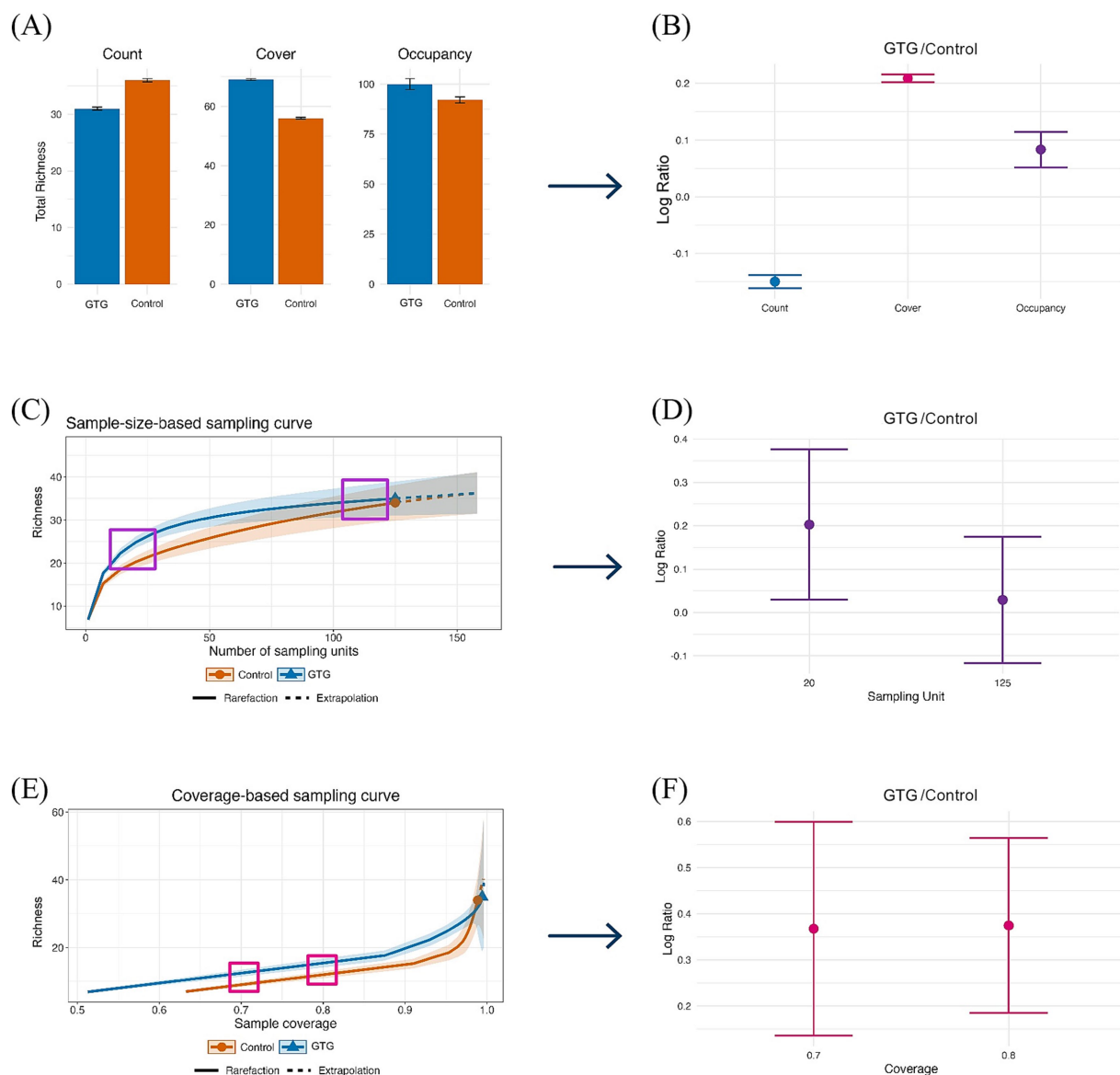


FIGURE 2

Comparison of biodiversity between GTG and Control seawalls 1 year after installation. **(A)** Species richness (y-axis) measured using three different methods—percent cover, counts of individuals, and occupancy (x-axis). **(B)** Log ratio of species richness (y-axis) between GTG and Control seawalls, shown across the three survey methods (x-axis). Values above zero indicate GTG supported more species. Error bars show standard error. **(C)** Rarefaction curves showing estimated species richness (y-axis) as a function of the number of sampling units (x-axis). Curves illustrate how richness increases with additional sampling effort. **(D)** Log ratio of species richness (y-axis) between GTG and Control seawalls, calculated at two fixed sample sizes (x-axis: 20 and 125 units, marked in panel C). **(E)** Coverage-based rarefaction curves showing species richness (y-axis) as a function of sample coverage (x-axis, ranging from 0 to 1, where higher values mean more complete sampling of the community). **(F)** Log ratio of species richness (y-axis) between GTG and Control seawalls, calculated at two coverage levels (x-axis: 0.7 and 0.8, marked in panel E).

organisms), each cell should identify the presence or absence of these species (Van Genne and Scrosati, 2022).

We illustrate this approach using the Port of Vigo case study. To reformat the Port of Vigo case study data, we divided the digital photographic quadrats into 5 cm by 5 cm boxes and identified the presence or absence of species. The scheme chosen to determine presence within the quadrat should be carefully considered and uniform throughout the study, to avoid overestimation or underestimation (Zvuloni et al., 2008). To deal with the borders of the quadrat, we employed a center rule scheme, where organisms that had their respective ‘center’ within the quadrat were counted

(Zvuloni et al., 2008). In situations with many species present, this process could be expedited by carefully choosing an artificial intelligence software to help identify and count species (Goodwin et al., 2022).

Using this occupancy approach promotes consistency in data collection across various contexts and facilitates easier comparisons over time or between locations. For instance, Figures 2A,B, which are based on photo-quadrat analysis of the GTG-enhanced seawall and the standard concrete seawall in the Port of Vigo, present contrasting views of the structure’s richness. For instance, determining which infrastructure offers greater richness depends on the data output

selected. If researchers only recognize “counted” species, the GTG infrastructure would seem to have lower richness (Figures 2A,B). Conversely, if they only recognize “cover,” the richness would appear artificially higher. Using occupancy combines the different sampling methods and allows us to estimate a single ratio between the GTG structure and the control (Figures 2A,B). The occupancy metric provides an essential, comparable framework for assessing the effectiveness of EcoTech’s application on the GTG infrastructure. By integrating both count and cover data, this metric offers a streamlined view of the sampled community, serving as a vital tool for evaluating ecological outcomes across diverse sites.

2.4 Standardized sampling effort

All diversity estimates are both scale-dependent and sampling effort-dependent. Hence, the perceived increase in diversity of a GTG EcoTech initiative will depend on the sampling method and sampling effort (Gotelli and Colwell, 2001; Chase and Knight, 2013). It is important to note that we rarely estimate all individuals and species on marine infrastructure, and hence, reaching an asymptotic relationship between sampling effort and diversity measures is an unrealistic goal. Instead, we suggest using a coverage-based rarefaction approach, a statistical technique used to estimate sample completeness by focusing on the proportion of individuals in a sample that is part of the identified species (Chao and Jost, 2012). Coverage-based rarefaction works by statistically estimating the species richness, diversity, or functional diversity of a community at a standardized level of sample coverage. Coverage-based rarefaction adjusts for differences in sampling effort, ensuring comparability between datasets of varying sizes (Chao and Jost, 2012). This enables us to evaluate sampling completeness with increasing sample size, and then compare the efficiency of GTG EcoTech applied on an infrastructure and control one at the same coverage level.

A notable benefit of the coverage-based approach is that the comparisons of the control marine infrastructure to the one presenting GTG EcoTech can be normalized for sampling effort. When sampling effort is by the number of individuals, as done when using traditional rarefaction, the ratio between the control and EcoTech applied structure diversity will depend on the exact sampling effort used. Figures 2C,D illustrate that the log ratio between the richness of the EcoTech applied structure and the control ones depends on the value of the sampling effort chosen for comparison. In practical terms, this means that the apparent difference in species richness can shift depending on how many samples are collected, which complicates direct comparisons. However, with coverage-based rarefaction, the same proportional increase in richness can be found at different coverage levels. For instance, a 20% increase in species richness can be consistently observed at both 50 and 90% coverage levels (Figures 2E,F). By accounting for how completely the community has been sampled, rather than just the number of individuals sampled, coverage-based methods provide more stable and comparable results. This allows for comparability between the EcoTech and control sites across varying sampling efforts or monitoring levels. This approach can be applied to other community-level measures, such as functional, evolutionary, or phylogenetic diversity (Chao et al., 2021), which are all crucial factors in assessing the infrastructure’s success. Thus, by focusing on coverage rather than just the

number of samples or individuals, these methods enhance the reliability of ecological assessments.

It is important to note that GTG and control sites may achieve similar levels of sample completeness at very different levels of sampling effort (Chao and Jost, 2012). Thus, in many cases, the less complex control site may need fewer samples to reach a similar level of coverage. This is a substantial benefit as it means there is no need to put unnecessary effort into sampling the simple control sites, and proportionally more effort can go into the often more complex GTG structures where the Ecotech is applied.

Nonetheless, it is crucial to avoid very low coverage values for comparison, as they may undermine the reliability of the estimates. We suggest using the iNEXT4steps package in R (Chao and Hu, 2024) to facilitate coverage-based rarefaction, as it provides tools for estimating species diversity, visualizing coverage curves, and effectively comparing biodiversity across different samples; Additionally, this package in R enables the integration of Hill numbers (Hsieh et al., 2016; Chao et al., 2014), to quantify diversity using the “effective number of species” taking into account different weights of richness versus evenness when calculating diversity (Chao et al., 2014). Specifically, Hill numbers represent $q = 0$ represents species richness (all species weighted equally), $q = 1$ is sensitive to typical species’ abundance (exponential of Shannon entropy), and $q = 2$ is sensitive to dominant species’ abundance (inverse Simpson index).

3 Conclusion

By outlining several key steps, including appropriate controls, using occupancy data to combine count and coverage, and employing coverage-based rarefaction, we can generate comparable estimates of the diversity benefits of GTG structures. These estimates can be obtained regardless of spatial location (tropical versus temperate regions, regions under different anthropogenic pressures, etc.), and structure type (seawalls to breakwaters, artificial reefs, pier piles, or any other formations). For researchers, following this protocol entails selecting controls at a site, shaping data into occupancy, and analyzing using coverage-based rarefaction. When doing so, to minimize bias in data collection, it is crucial to define clear rules for including or excluding species that straddle quadrat borders. Once coverage-based rarefaction information and biodiversity data are consolidated, a ratio of species richness (or other diversity measures) between the control and GTG treatment can be generated. This ratio can be effectively used to compare diverse GTG EcoTech applied sites, sampled in different locations and times, regardless of the type of structure or its location.

We note that there is inherent bias in oversimplifying complex ecological dynamics by solely relying on such metrics, as this may overlook critical nuances in species interactions, functional roles, and successional pathways. Therefore, a comprehensive understanding necessitates integrating several quantitative measures and the broader ecological context to avoid drawing misleading conclusions from simplified metrics.

The ability to assess the efficacy of GTG infrastructure can inform both national and international standards of “best practice.” From a policy and regulatory perspective, establishing core, standardized indicators for biodiversity, ecosystem services, and design performance can support the adoption of GTG monitoring frameworks within existing directives such as the EU Marine Strategy Framework Directive and the UN Sustainable Development Goal 14.

By aligning monitoring protocols with these frameworks, projects can demonstrate measurable ecological benefits and reduce the risk of greenwashing, ensuring that claims of 'nature-inclusive infrastructure' are evidence-based. Flexible, tiered methodologies that combine global guiding principles (e.g., IUCN NbS Standard), regional or national adaptations, and project-specific ecological and social monitoring can enable decision-making across scales.

This comparative approach enables marine ecologists, developers, and stakeholders to collaboratively develop a scalable understanding of ecosystem services in various GTG projects. The insights into streamlined comparisons are crucial for effective EcoTech initiatives, facilitating informed decision-making and efficient resource management. Practitioners, organizations, and policymakers should work together to create usable and widely adopted data analysis protocols.

Author contributions

AL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. YR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JB: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. IS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

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AL, YR, and IS were employed by EConcrete Inc.

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