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Developing a Preliminary MEL–DPSIR Framework for Future Assessment of Seagrass Restoration Effectiveness: The Case of Cu Lao Cham Nature Reserve, Vietnam

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Abstract

Assessing seagrass restoration requires looking beyond biological recovery to include environmental, social, and management factors. To address this in Cu Lao Cham Nature Reserve, Vietnam, we developed a 31-indicator Monitoring–Evaluation–Learning and Drivers–Pressures–State–Impact–Response (MEL–DPSIR) framework spanning five key dimensions. We derived indicator targets from international standards, national policy, baseline data, and local stakeholder input. Using a fuzzy multi-criteria evaluation, the Biological–Ecological dimension received the highest integrated weight (0.34), followed by Community Livelihoods (0.28), while Learning received the lowest weight (0.05)—a ranking that proved robust under sensitivity testing. Because empirical restoration data are not yet available, this paper presents the framework design rather than empirical testing. Ultimately, our framework offers a flexible decision-support tool meant to be refined through real-world monitoring cycles.

Keywords: seagrass restoration; composite indicators; fuzzy AHP; adaptive management; social–ecological systems

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1. Introduction

Seagrass meadows underpin a wide range of ecological and societal benefits: they provide habitat for marine species, stabilise shorelines, regulate water quality, support nutrient cycling, and store significant amounts of blue carbon [1–3]. Despite this, seagrass ecosystems are declining worldwide as a result of coastal development, pollution, destructive fishing practices, tourism pressure, and climate change [2,3]. Restoring these ecosystems has therefore become an urgent conservation priority. Evaluating how effective such restoration actually is, however, remains particularly challenging, since ecological recovery, environmental conditions, human pressures, community benefits, and management responses do not change in step with one another—they shift at different rates and sometimes in opposite directions.

Most restoration assessments still rely heavily on ecological indicators—such as meadow area, cover, and biomass [2,4,5]. While essential, these metrics provide only a partial picture; ecological gains are unlikely to persist if underlying human pressures remain unmanaged, local communities derive no benefits, or monitoring fails to inform adaptive practice [6–10]. Restoration effectiveness is therefore better understood as a social–ecological process rather than simply biological recovery. However, three major gaps persist in current approaches. First, an outcome-scope gap: assessments remain predominantly biophysical, overlooking livelihoods, governance, and learning. Second, a causal-learning gap: existing frameworks rarely trace outcomes to their root causes or provide structured feedback for management. Third, a contextual-operational gap: internationally developed guidance often fails to translate directly to sites with distinct ecological baselines, regulatory standards, and institutional capacities.

The DPSIR (Drivers–Pressures–State–Impact–Response) framework and the MEL (Monitoring–Evaluation–Learning) cycle offer complementary solutions to these gaps: DPSIR traces causal chains from human drivers to management responses, while MEL links monitoring evidence to adaptive learning [11]. Integrating the two allows causal diagnosis and management learning to reinforce each other. This approach is particularly needed in Vietnam, where seagrass research has focused largely on ecological distribution [12], leaving the underlying drivers and institutional responses at sites like Cu Lao Cham Nature Reserve largely unexamined [13,14]. Moreover, international guidelines must be carefully adapted to local ecological baselines, regulatory standards, and institutional capacities rather than adopted as-is [11,12,15].

The principal novelty of this work extends beyond combining existing approaches; it lies in the operationalisation of this integration into a quantitative, context-specific decision-support tool. Rather than offering another qualitative checklist, this study translates broad international guidelines into a weighted, multi-dimensional composite scoring system tailored for seagrass social–ecological restoration. By explicitly linking causal drivers (DPSIR) to measurable feedback loops (MEL) and incorporating participatory weighting with stakeholder engagement, the framework provides managers with a structured diagnostic tool that not only tracks biological symptoms but also helps diagnose potential underlying pressures and management factors, and triggers targeted, evidence-based management responses.

This study is guided by three research questions. The first concerns scope: which dimensions—covering ecology, environmental conditions, social outcomes, management practice, and institutional learning—are actually needed to capture seagrass restoration at Cu Lao Cham Nature Reserve as a social–ecological process rather than a purely biological one? The second question is more methodological: how can DPSIR's causal structure be paired with MEL's feedback-oriented logic in a way that produces an indicator framework genuinely suited to monitoring restoration and supporting adaptive management in this setting? The third turns to implementation: once indicator groups have been identified, how should they be prioritised, and through what channels could the framework realistically be integrated into local protected-area management?

To answer these questions, the study develops a MEL–DPSIR framework that links DPSIR's diagnostic logic with MEL's focus on adaptive learning. Indicators were selected and prioritised through expert assessment and stakeholder consultation, while weighting and aggregation followed standard composite-indicator principles. In practical terms, the framework contributes by linking causal diagnosis with learning-oriented feedback, translating restoration effectiveness into measurable terms across ecological, social, and institutional dimensions, and outlining how the framework could be integrated into routine protected-area monitoring and management at Cu Lao Cham. It is important to clarify,

however, that the framework is not yet an empirically validated assessment tool. Rather, it should be understood as a context-specific basis for monitoring and decision-making at this site. Because the restoration project is still in its early stages, its real-world value will need to be confirmed through repeated monitoring cycles and continued field application.

2. Materials and Methods

2.1. Study Area and Institutional Context

Cu Lao Cham Nature Reserve was established from the former Cu Lao Cham MPA, with an expanded mandate that integrates the management of island forests, marine ecosystems, and coastal resources. The reserve covers approximately 23,530 ha and was formerly administered by Hoi An City, Quang Nam Province. Following the 2025 administrative merger of Quang Nam Province and Da Nang City, it now falls within Da Nang City. It comprises four functional zones: Strictly Protected Zone (569.04 ha), Ecological Restoration Zone (1147.81 ha), Service and Administration Zone (10,260.27 ha), and Buffer Zone (11,552.82 ha). The island system includes seven islands—Lao, Cu, Kho, La, Dai, Mo, and Tai—with Lao Island being the largest, at approximately 1147 ha [16].

Cu Lao Cham seagrass meadows have undergone substantial spatial and temporal change. Total meadow area increased from 55.98 ha in 2003 to 74.38 ha in 2010, reflecting approximately 40.2 ha of loss but 58.6 ha of new formation or recovery. This trend then reversed sharply, with 68.90 ha lost and only 7.30 ha recovered between 2010 and 2017, reducing total area to 12.78 ha. By 2025, the remaining meadow area was 12.3 ha, indicating that the system has persisted at a substantially reduced extent [13,14,16]. These changes highlight the vulnerability of the reserve's seagrass ecosystems and provide a strong basis for developing a MEL–DPSIR framework suited to local ecological conditions, monitoring capacity, and social priorities.

The 2025 seagrass distribution map shown in Figure 1 was derived from Sentinel-2A Level-1C imagery acquired on 7 June 2025 at 10 m spatial resolution. Image preprocessing was conducted in ACOLITE (version 20251013.0) using Dark Spectrum Fitting, followed by K-means masking and Lyzenga depth-invariant transformation. Seagrass was classified using a Support Vector Machine and validated against 185 georeferenced field points collected in August 2025 and March–June 2026. Classification accuracy reached 92% (Kappa = 0.89), and final spatial processing and map preparation were completed in QGIS (version 3.44.13 "Solothurn"). The temporal offset between image acquisition and field validation is acknowledged as a potential source of uncertainty.

Recent degradation reflects the combined effects of seabed instability and disturbance, sediment deposition, tourism-related vessel activity and anchoring, localised wastewater pollution, and epiphytic algal growth [16]. These pressures are especially evident at Bai Ong and Bai Huong, while changes at Bai Bim and Mo Island may also reflect local hydrodynamic and substrate instability [16]. In this study, the 2003 extent is used only as a historical reference point, whereas the 2025 extent of 12.3 ha represents the contemporary project baseline for assessing subsequent restoration-related changes.

The restoration initiative is intended to support the recovery of degraded seagrass habitat within Cu Lao Cham Nature Reserve while generating information for adaptive management and future scaling. The intervention is planned within degraded seagrass areas identified through project surveys and local management priorities. As the present study focuses on developing the MEL–DPSIR framework rather than evaluating restoration outcomes, the restoration technique and intervention layout are described only to the extent currently defined by the project. Pre-intervention conditions within the restoration area constitute the initial project baseline for future evaluation. As formal control and natural reference meadows have not yet been fully established, the cur-

rent study utilizes a baseline-referenced approach; however, future implementation should adopt a Before–After–Control–Impact (BACI) or equivalent comparative design, incorporating ecologically comparable non-restored and/or natural reference sites to rigorously attribute observed changes to the restoration intervention rather than to natural variability or external pressures.

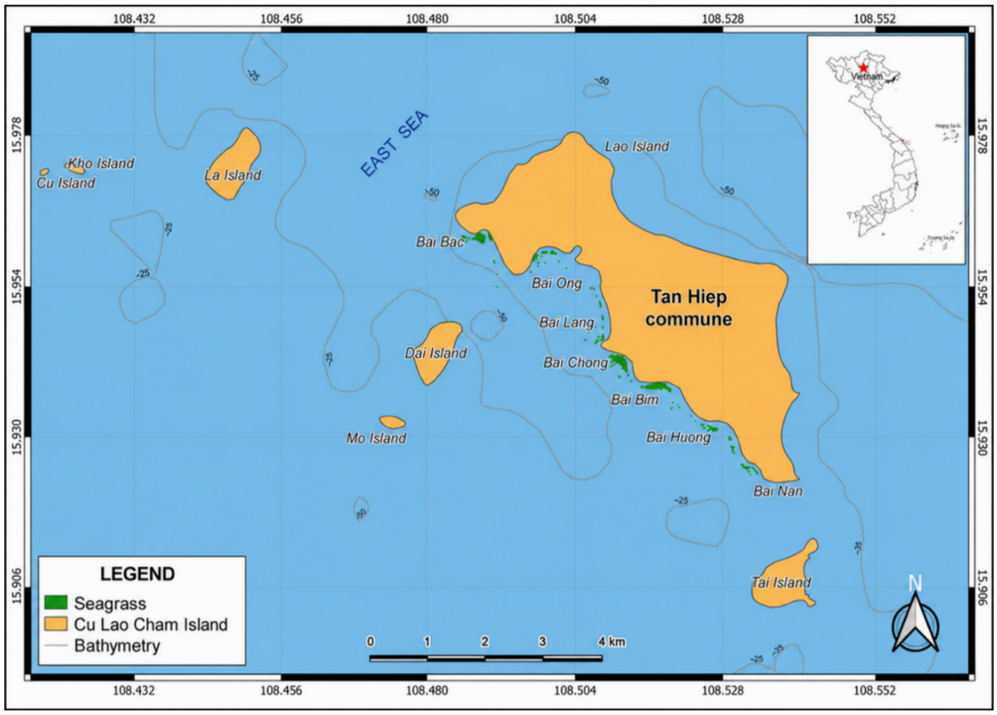


Figure 1. Spatial distribution of seagrass beds in Cu Lao Cham Nature Reserve in 2025, with bathymetric contours.

From an institutional perspective, Cu Lao Cham Nature Reserve is also a suitable setting for developing a restoration assessment framework that can be linked to local management practice. National and local policy instruments in Vietnam already provide a broad foundation for biodiversity conservation, ecosystem restoration, environmental monitoring, habitat protection, and community participation [15,17–19].

However, existing policy instruments and site-level monitoring routines do not yet provide a dedicated protocol for assessing seagrass restoration effectiveness or standard thresholds for most livelihood, governance, and adaptive-learning indicators. The proposed framework was therefore designed to build on existing biodiversity and environmental monitoring activities by adding a seagrass-restoration-specific assessment layer, rather than replacing formal regulatory instruments. Where applicable, recognised national standards were incorporated directly, including QCVN 10:2023/BTNMT for selected marine water-quality indicators [20].

At the local level, the Cu Lao Cham Nature Reserve Management Board is the natural institutional entry point for putting the framework into practice. Its mandate already covers biodiversity conservation and environmental protection, extends to ecological restoration and scientific research, and reaches into ecotourism and sustainable development as well [16]. This broader mandate shaped how indicators, data sources, monitoring frequencies, and targets were chosen—particularly indicators touching on environmental quality and management effectiveness on the one hand, and community participation, livelihood benefits, and adaptive learning on the other.

2.2. Development of the MEL–DPSIR Indicator Framework

The MEL–DPSIR indicator framework was developed through a five-step process designed to keep the assessment scientifically grounded while remaining practical for local application (Figure 2). The process began with the definition of project objectives and evaluation questions, followed by the development of indicators across five thematic groups. For each indicator, measurement methods, monitoring frequencies, data sources, proposed targets, and reference bases were specified. The draft framework was subsequently reviewed and refined through expert and stakeholder consultation. This process drew on seagrass monitoring guidance [2,4,5], conservation and MPA evaluation guidance [21], relevant provisions of QCVN 10:2023/BTNMT [20], site-level baseline data, expert judgement, local stakeholder input, and the objectives of the WWF-supported restoration project.

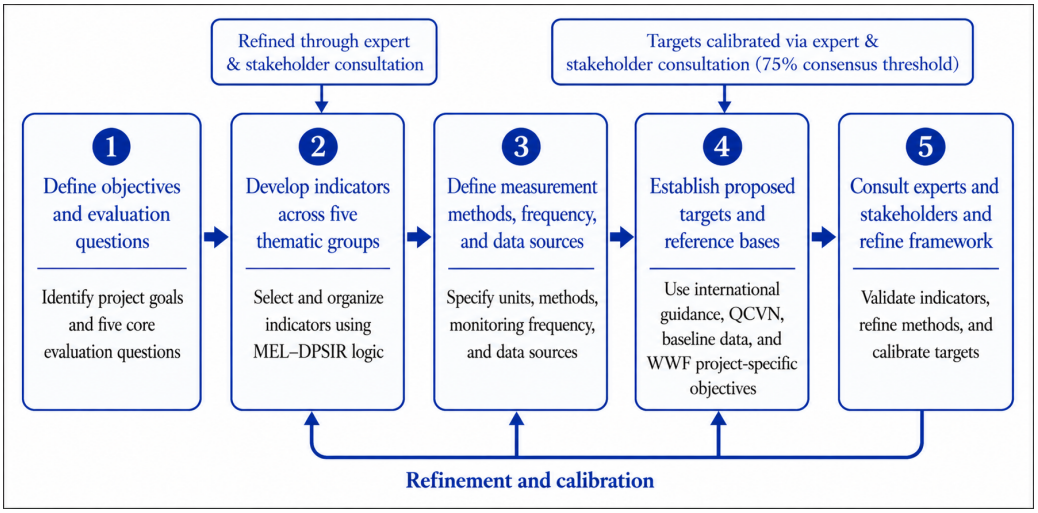


Figure 2. Five-step process for developing the MEL–DPSIR indicator framework, showing how expert and stakeholder consultation informed indicator selection and target calibration.

In Step 5, the draft framework was reviewed through a purposive and context-specific consultation process involving 15 experts and 20 local stakeholders. The experts were selected from the Nha Trang Institute of Oceanography, the Cu Lao Cham Nature Reserve Management Board, Hue University, and Da Nang City's Department of Agriculture and Environment for their experience in seagrass ecology, restoration practice, and environmental monitoring. The 20 local stakeholders comprised local authorities, tour operators, fishers, and community representatives. To ensure transparency, a structured, multi-track protocol was applied: experts validated ecological and technical soundness, while stakeholders assessed social feasibility and local applicability.

Target values were finalised in a joint plenary using a five-point agreement scale. A target was adopted only if it received at least 75% agreement from both groups. Where consensus was lacking, divergent viewpoints were resolved through structured qualitative discussion rather than formal quantitative metrics. Participants evaluated proposed targets against the strongest available evidence, including national regulations (e.g., QCVN 10:2023/BTNMT), published guidance, and baseline data. Scientific plausibility guided expert evaluations, while operational feasibility directed stakeholder feedback. Targets were iteratively refined until the 75% threshold was reached. Following this, outputs were systematically cross-checked against regulatory and baseline references before final approval. Consequently, thresholds lacking strict regulatory foundations are treated as context-specific and provisional.

Figure 3 illustrates the conceptual integration of the MEL cycle and DPSIR framework, showing how the five indicator groups collectively link ecological conditions, social

outcomes, management responses, and adaptive learning within a unified restoration assessment framework.

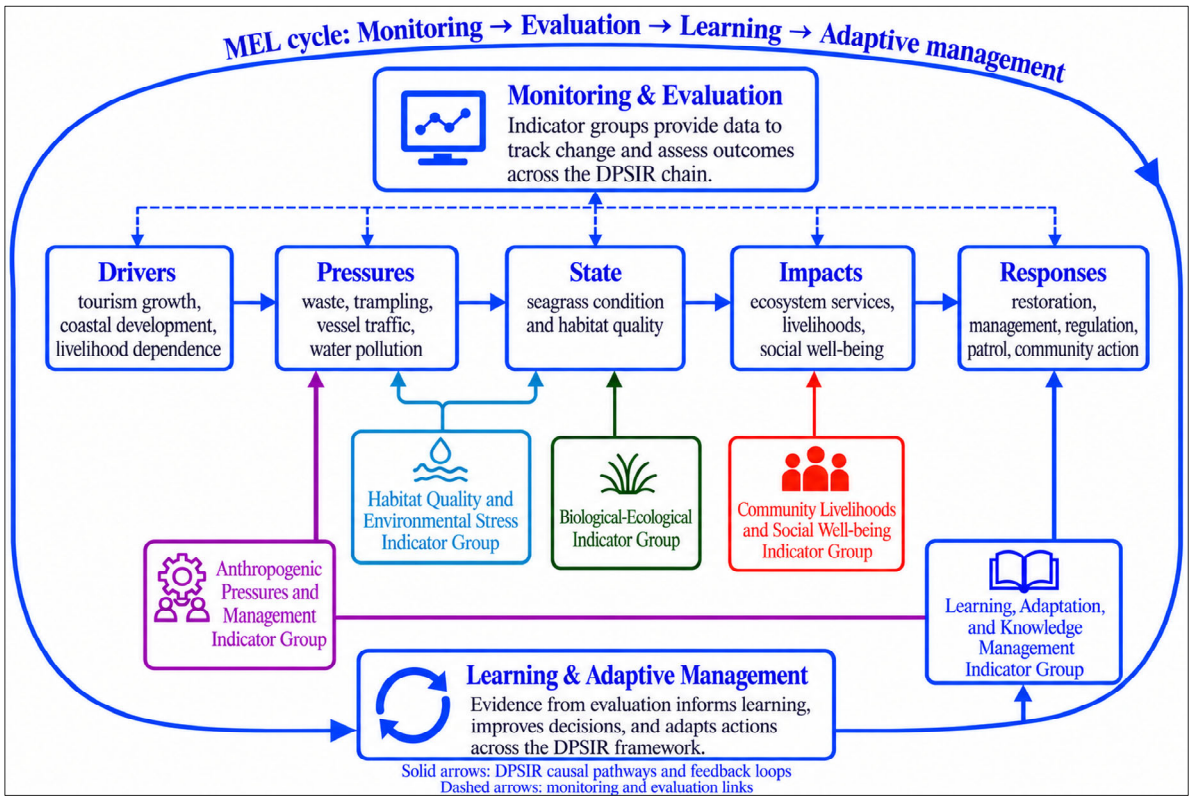


Figure 3. MEL–DPSIR conceptual framework linked to five indicator groups.

To make the framework truly operational, each of the 31 indicators was explicitly linked to its practical implementation requirements. Specifically, we defined the primary data sources, assigned lead and supporting institutional responsibilities, established monitoring frequencies, and prescribed specific management decisions to be triggered if a target is not met. This comprehensive operational matrix is provided in Supplementary Material S1.

Note on target justification: Proposed targets differ in their evidentiary basis. Regulatory thresholds were used where applicable; otherwise, targets were derived from published guidance, project objectives, site-specific baseline conditions, and expert/stakeholder judgement. Targets without formal technical standards should be regarded as context-specific and provisional, and should be recalibrated as repeated monitoring data become available.

2.3. Weighting Procedure

Weights were assigned at the indicator-group level rather than to individual indicators. This approach was used to keep the assessment process manageable, reduce the consultative burden on participants, and limit the influence of fluctuations in any single indicator [22]. It is also consistent with composite indicator development, where weights commonly represent the relative importance of major assessment dimensions rather than variations among individual indicators [22].

The weighting procedure drew on two sources of input: expert judgement and stakeholder preferences. Expert-derived group weights were obtained using the Fuzzy Analytic Hierarchy Process (Fuzzy AHP), while stakeholder-derived group weights were generated using a fuzzy Likert-scale approach. In both approaches, fuzzy linguistic assessments were used to accommodate uncertainty and vagueness in preference elicitation [23,24]. Figure 4

summarises the procedure used to derive and integrate the expert- and stakeholder-derived weights.

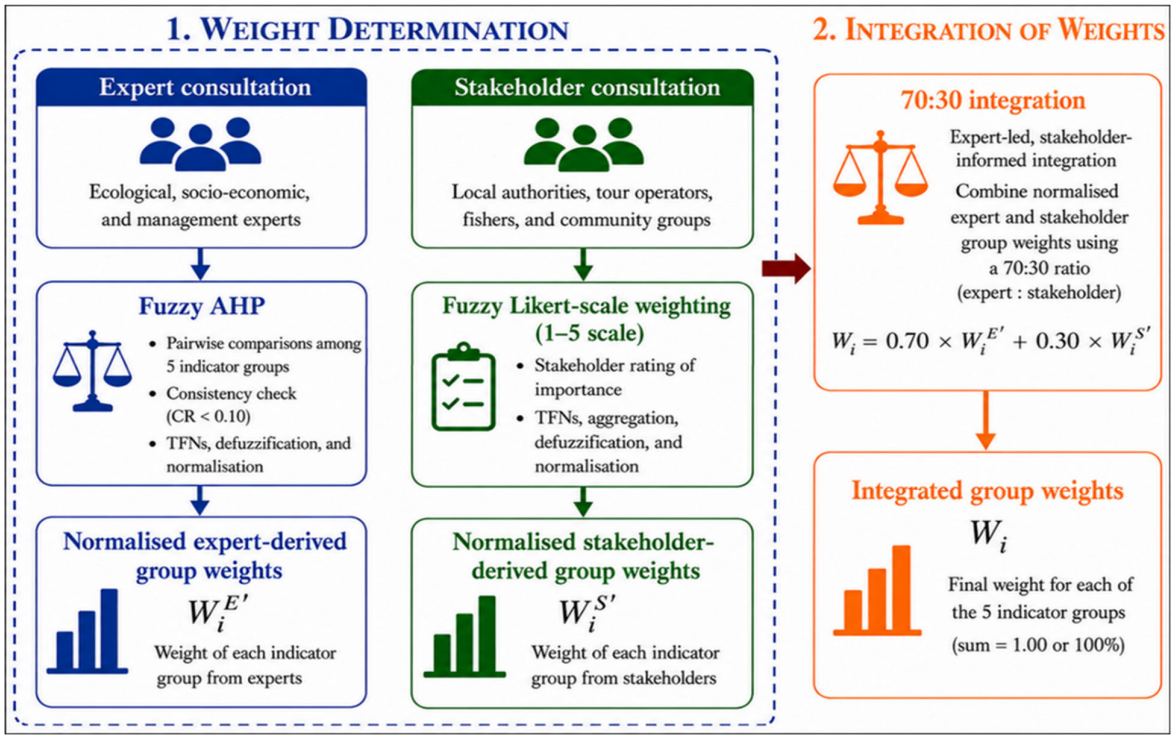


Figure 4. Procedure for deriving and integrating expert- and stakeholder-based weights for the five indicator groups.

Following the consultation workshop described in Section 2.2, the same expert panel was asked to conduct pairwise comparisons among the five indicator groups using Saaty's 1–9 scale [25]. Each comparison value was converted into a Triangular Fuzzy Number (TFN)—for example, 3 = (2, 3, 4) and 5 = (4, 5, 6)—to account for uncertainty in expert judgement [24,26,27]. Before fuzzy aggregation, the consistency of each expert's original pairwise-comparison matrix was checked using the Consistency Ratio (CR), with CR < 0.10 considered acceptable. The validated fuzzy comparisons were then aggregated, defuzzified using the centroid method, and normalised to obtain the final expert-derived group weights [24,27]. To support methodological transparency and reproducibility, Supplementary Material S2 provides the verified expert-derived normalised weights, the integration of expert and stakeholder weights, and consistency-check results for all 15 experts (CR < 0.10). The individual pairwise-comparison matrices are retained as project records and are available from the corresponding author upon reasonable request.

For the stakeholder consultation, participants rated the importance of each indicator group on a five-point Likert scale during the workshops. To reflect ambiguity in stakeholder preferences, these ratings were mapped onto TFNs, such as 1 = (0, 1, 2), 3 = (2, 3, 4), and 5 = (4, 5, 6). The fuzzy preference scores were then aggregated across all respondents, defuzzified using the centroid method, and normalised to obtain the stakeholder-derived group weights.

The final integrated weight of each indicator group was calculated by combining the normalised expert-derived and stakeholder-derived weights using a 70:30 ratio:

$$W_i = 0.70 \times W'_{iE} + 0.30 \times W'_{iS} \quad (1)$$

where W_i is the integrated weight of indicator group i, W'_{iE} is the normalised expert-derived weight, and W'_{iS} is the normalised stakeholder-derived weight.

To our knowledge, there is no universally established expert-to-stakeholder ratio for seagrass restoration assessment. The 70:30 ratio was adopted as an author-defined, context-specific weighting assumption. It gives greater weight to technical expertise in view of the State's regulatory responsibilities, while retaining substantial stakeholder influence consistent with national policy emphasis on participation and co-management [15,17–19]. This ratio balances technical regulatory authority with the social licence to operate, and should be read as a transparent, context-specific working assumption rather than a universal standard.

To verify that the prioritisation of indicator groups did not depend exclusively on this base-case ratio, a sensitivity analysis was conducted using alternative expert-to-stakeholder ratios of 50:50, 60:40, and 80:20. Because complete monitoring data were not yet available at this stage, this analysis was limited to testing the robustness of the group-weight prioritisation; it did not extend to changes in the final project-effectiveness score or performance-band classification. Nevertheless, the results confirmed that the rank order of the five indicator groups remains stable across all tested scenarios, demonstrating that the final prioritisation holds up well and is not overly sensitive to the chosen 70:30 integration ratio.

2.4. Composite Assessment Method

The integrated group weights lay the groundwork for a composite scoring procedure, following established principles for constructing and interpreting composite indicators [22]. This procedure is meant for future monitoring cycles, once data across the five indicator groups are complete and comparable enough to support it. In practice, it would synthesise performance across those groups into a single screening-level score, on a scale of 0 to 100.

For each indicator group, the achievement rate would be calculated as the proportion of indicators meeting their proposed targets:

$$A_g = \frac{n_g}{N_g} \times 100 \tag{2}$$

where A_g is the achievement rate of indicator group g, n_g is the number of indicators meeting their proposed targets, and N_g is the total number of indicators in that group.

The contribution score of each indicator group would then be calculated by multiplying the achievement rate by the corresponding integrated group weight:

$$C_g = A_g \times W_g \tag{3}$$

where C_g is the contribution score of indicator group g, and W_g is the integrated group weight derived from the weighting process.

The total project effectiveness score would be obtained by summing the contribution scores across the five indicator groups:

$$T = \sum_{g=1}^{5} C_g \tag{4}$$

where T is the total project restoration effectiveness score on a scale of 0–100.

The final composite score is classified into four provisional performance bands: Poor (<50), Moderate (50–69), Good (70–84), and Excellent (≥85). These breakpoints were defined by the authors as a screening-oriented interpretive scheme, informed by principles of transparency, interpretability, context-sensitive judgement, and decision relevance in composite-indicator assessment [22,28,29]. Specifically, scores below 50 indicate generally

weak overall performance; 50–69 indicate moderate performance with substantial room for improvement; 70–84 indicate generally good performance across most weighted targets; and ≥85 indicate high overall target achievement. The bands are intended to support rapid management interpretation rather than to serve as universal ecological benchmarks.

This composite scoring approach is a screening-level tool, kept deliberately simple, transparent, and practical for local managers to use. Each indicator is scored simply by whether its target has been met, which keeps the method usable without heavy data processing. For indicators with expected ecological time-lags, such as species composition and belowground biomass, early monitoring results should be interpreted as directional evidence rather than as definitive evidence of success or failure. The framework as a whole is still an initial decision-support tool at this point, and confirming its reliability will require repeated monitoring cycles and further field data.

The composite scoring procedure itself was not applied in this study, simply because complete and comparable data were not yet available across the five indicator groups. It is meant, instead, for future assessment phases—once baseline data have been consolidated and verified.

3. Results

3.1. Indicator Groups and Specific Indicators

3.1.1. Biological–Ecological Indicator Group

Six biological–ecological indicators were retained to assess whether restoration produces measurable recovery in the spatial extent, structural condition, species composition, and plant performance of seagrass meadows. As summarised in Table 1, seagrass meadow area and percentage cover capture recovery at the meadow scale, while shoot density, mean leaf length, and above- and below-ground biomass provide information on plant condition and development. Species composition was included to determine whether restoration maintains or improves the presence of native seagrass species.

The consultation process confirmed that these indicators provide direct evidence of ecological restoration outcomes. Experts emphasised the need to combine broad-scale indicators, such as meadow area and cover, with field-based indicators capable of detecting changes in meadow structure and plant condition. Local stakeholders and management staff particularly valued area and cover because they are relatively easy to monitor and communicate. All biological and structural indicators (seagrass coverage, shoot density, mean leaf length, biomass, and species composition) should therefore be prioritised during the April–August peak-growth period, which represents the optimal growing season for seagrass in Cu Lao Cham.

Targets were set using two complementary reference approaches. Where defensible numerical benchmarks existed—for meadow expansion and peak-season seagrass cover, for instance—project-specific and guidance-based targets were applied directly. The 10% increase in meadow area, in particular, was treated as a cautious early-stage benchmark. This reflects several realities on the ground: the assessment period itself is short, just two years; Cu Lao Cham's seagrass beds show natural spatial variability; *Thalassia hemprichii* expands clonally and slowly; and local conditions—bathymetry, substrate, and available restoration space—impose their own limits.

Other indicators, including shoot density, species composition, leaf length, and biomass, were instead judged against the initial project baseline, since these vary with species traits, seasonality, and site conditions. Where baseline conditions are already reasonably stable, simply maintaining them may be an acceptable outcome; where conditions started out degraded, actual improvement is expected. There is currently no Vietnamese

technical threshold for biological recovery in seagrass restoration to draw on, which is why baseline-based targets were used here instead of a universal fixed value.

Table 1. Core indicators and proposed targets for theBiological–Ecological Indicator Group.

Indicator	Unit	Measurement Method	Frequency	Proposed Target	Reference/Target Basis
Seagrass meadow area	ha	Satellite image interpretation with GPS field verification and GIS mapping	Twice per year, with remote-sensing support and targeted field verification	≥10% net increase from the 2025 baseline of 12.3 ha after two years, as an early-stage project benchmark	WWF project-specific target and baseline field survey *
Seagrass coverage	%	Quadrat sampling and/or seabed photography	Twice per year	≥50% from April to August **	Expert/stakeholder judgement and Cu Lao Cham baseline conditions
Shoot density	shoots/m^2	Count shoots in 0.25 m^2 quadrats with 3–5 replicates per site	Twice per year	Maintain or increase relative to the initial project baseline	[5] and baseline field survey
Species composition	Number of species	Photography, specimen collection and identification	Annually	Maintain or increase the number of native seagrass species relative to the initial project baseline	[4] and baseline field survey
Mean leaf length	cm	Field measurement of dominant seagrass species	Twice per year	Maintain or increase relative to the initial project baseline ***	[4] and baseline field survey
Above- and below-ground biomass	kg dry weight m^{-2}	Samples are dried at 60 °C to constant weight and weighed	Annually	Maintain or increase relative to the initial project baseline	[5] and baseline field survey

Note: * Baseline data refer to pre-intervention conditions established during the initial project monitoring period; subsequent assessments should evaluate trends relative to this baseline. ** The seagrass meadows in Cu Lao Cham experience their peak growth from April to August. *** Mean leaf length should be interpreted for the dominant species (*Thalassia hemprichii*) in Cu Lao Cham and compared with the initial project baseline.

3.1.2. Habitat Quality and Environmental Stress Indicator Group

To determine whether environmental conditions remain suitable for the survival and growth of restored seagrass meadows, six indicators were retained (Table 2). Water transparency was selected to track light availability, while pH and dissolved oxygen serve as baseline metrics for general water quality. Nutrient enrichment is monitored through ammonium and phosphate concentrations. Finally, total suspended solids capture turbidity and sediment disturbance, complementing sediment organic matter as a measure of seabed organic accumulation.

The monitoring frequencies proposed here are best treated as a minimum, adaptive schedule, rather than a rigid schedule. To keep the workload manageable for the Management Board, routine habitat-quality monitoring could run twice a year, timed around the April–August peak-growth period and one contrasting season, with extra targeted sampling added after storms, pollution events, unusual turbidity, or periods of heavy tourist activity.

This indicator group was designed to complement the biological–ecological indicators, detecting environmental stress before it manifests as seagrass decline. During consultations, experts and stakeholders flagged water clarity, wastewater influence, tourism activity, and vessel disturbance as the concerns most relevant locally. These indicators were kept in the framework for two primary reasons: they are ecologically critical, and they provide managers with practical diagnostic tools to identify the actual drivers affecting restoration on the ground.

Table 2. Core indicators and proposed targets for the Habitat Quality and Environmental Stress Indicator Group.

Indicator	Unit	Measurement Method	Frequency	Proposed Target	Reference/Target Basis
Water transparency	m	Secchi disk measurement in the field	Twice per year, prioritising the April–August peak-growth period and one contrasting seasonal period	Maintain or increase relative to the initial project baseline	[4] and baseline field survey
pH	–	Multi-parameter meter or pH pen	Twice per year, with additional measurement after pollution events or abnormal water conditions	6.5–8.5	[20]
Dissolved oxygen (DO)	mg/L	Multi-parameter meter	Twice per year, with additional measurement after pollution events, algal blooms, or fish-mortality events	≥5 mg/L	[20]
NH_4^+ and PO_4^{3-} concentration	mg/L	Rapid test kit or laboratory sample analysis	Twice per year, with additional sampling during pollution events or peak tourist periods	NH_4^+-N ≤ 0.1 mg/L; PO_4^{3-}-P ≤ 0.2 mg/L	[20]
Total Suspended Solids (TSS)	mg/L	Filter through 0.45 µm membrane, dry at 105 °C and weigh	Twice per year, with additional sampling during pollution events or peak tourist periods	≤50 mg/L	[20]
Sediment organic matter content	%	Laboratory analysis using Loss on Ignition (LOI) method	Annually	Maintain at or below the site-specific initial project baseline	[5] and baseline field survey

Note: QCVN 10:2023/BTNMT-based thresholds were applied to marine water quality parameters where available. Baseline-based targets were used for indicators without direct regulatory thresholds, such as water transparency and sediment organic matter.

Target setting combined nationally recognised standards with site-specific baseline values. Thresholds for pH, dissolved oxygen, NH_4^+, PO_4^{3-}, and TSS were referenced against QCVN 10:2023/BTNMT. Water transparency and sediment organic matter were assessed relative to the initial project baseline because no directly applicable national thresholds exist for these site-specific habitat characteristics. This combined approach allows the framework to distinguish compliance with national marine water-quality standards from changes in local environmental conditions. The group therefore acts as an early-warning signal, helping managers judge whether weak biological recovery stems from water-quality decline, reduced light, nutrient enrichment, or sediment disturbance.

3.1.3. Community Livelihoods and Social Well-Being Indicator Group

To assess whether seagrass restoration produces meaningful social benefits and fosters stronger community support for long-term conservation, six indicators were retained. As presented in Table 3, these cover participation in sustainable livelihood activities, household income, seagrass-linked ecotourism, conservation awareness, household involvement in conservation efforts, and the inclusion of women and vulnerable groups.

Consultations with experts and stakeholders indicated that ecological restoration is unlikely to be sustained over time unless local communities participate meaningfully, derive tangible benefits, and develop a sense of ownership over the outcome. Local participants, for their part, kept coming back to a few things—concrete livelihood opportunities, better income, greater awareness of conservation, and a real say in management activities. Including women and vulnerable groups in this picture also lets the framework ask a further question: is access to restoration-related benefits actually inclusive, or does it favour some groups over others?

Table 3. Core indicators and proposed targets for the Community Livelihoods and Social Well-being Indicator Group.

Indicator	Unit	Measurement Method	Frequency	Proposed Target	Reference/Target Basis
Number of households participating in sustainable livelihood models	Households	Household survey/commune authority report	Annually	≥30 households by Year 2	WWF project logical framework and local stakeholder consultation
Average household income from sustainable seagrass-linked livelihoods	million VND household^{-1} year^{-1}	Household income survey	Annually	≥20% increase from the initial project baseline	Local stakeholder consultation
Number of seagrass-linked ecotourism tours	Tours	Tour registration records/commune authority report	Annually	≥50 tours/year by Year 2	Local stakeholder consultation and expert judgement
Community conservation awareness level	%	10-question knowledge test questionnaire	Annually	Average score ≥70% or ≥7/10 correct answers	Expert judgement
Proportion of households participating in conservation	%	Commune authority/Cu Lao Cham Management Board report	Annually	≥40% of households in project area	[21,30] and local stakeholder consultation
Proportion of women and vulnerable groups participating in conservation	%	Commune authority report	Annually	Increasing participation compared with the initial project baseline	[31,32] and local stakeholder consultation

Note: The proposed socio-economic targets are locally calibrated and project-specific rather than universal standards. They were developed based on relevant literature, expert judgement, local stakeholder consultation, and the livelihood context of Cu Lao Cham.

The targets here were built as locally calibrated benchmarks for this specific project rather than universal standards. Specific numerical thresholds (e.g., ≥30 households participating in livelihood models, ≥50 seagrass-linked tours per year) were derived directly from the WWF project's logical framework and validated by local stakeholders during the consultation as realistic Year-2 benchmarks, given the local demographic size and tourism carrying capacity. For indicators such as household income improvement and the participation of women and vulnerable groups, the initial project baseline was used instead of a fixed threshold, as a single fixed value would not adequately capture the real differences in local demographics and access across communities. Taken together, this indicator set is meant to show two things: whether restoration-associated activities coincide with or contribute to livelihood benefits, and whether it generates the kind of social legitimacy that lets conservation efforts last. Seagrass-linked ecotourism, in this context, means tourism kept low-impact and closely guided—steered away from sensitive restoration plots and kept within the site's visitor-control measures.

3.1.4. Anthropogenic Pressures and Management Indicator Group

Seven indicators were retained to assess both the human pressures affecting restored seagrass meadows and the capacity of local management systems to respond. As shown in Table 4, the group covers vessel and tourist density, shoreline plastic waste, trampling damage, conservation violations, patrol frequency, community and visitor compliance, and governance effectiveness.

Pressure indicators in this group are paired with corresponding response indicators, enabling managers to trace underperformance back to its root causes. On the pressure side, direct threats include high tourism intensity, trampling, waste accumulation, and conservation violations. On the response side, patrol frequency, compliance levels, and governance effectiveness reflect the adequacy of management interventions. Both experts and local stakeholders highlighted that these pressures peak during the tourist high season,

precisely when the most accessible seagrass areas face the greatest stress. To ensure data reliability, vessel and visitor-pressure figures should be cross-verified using multiple sources, including field observations, tour-operator logs, visitor records, Management Board reports, and, where available, camera-based data.

Table 4. Core indicators and proposed targets for the Anthropogenic Pressures and Management Indicator Group.

Indicator	Unit	Measurement Method	Frequency	Proposed Target	Reference/Target Basis
Vessel and tourist density at key restoration sites	Trips/month	Cross-checked field observations, vessel/tour-operator logs, visitor records, Management Board reports, and camera data where available	Twice per year, covering peak and off-season periods	Maintain at or below the initial project baseline in key restoration sites, unless an approved carrying-capacity threshold is established	[21,30] and local stakeholder consultation
Plastic waste density on shoreline transects	kg/100 m of shoreline	Shoreline transect survey, collection and weighing *	Twice per year, preferably after peak tourist or storm periods	≥20% reduction after 2 years compared with baseline	UNEP/IOC monitoring guidance [33] and expert judgement
Trampling damage from tourists	Score (1–5)	Rapid assessment using ordinal 1–5 damage scale **	Twice per year, prioritising the peak tourist season	≤2 at restoration sites	Local stakeholder consultation
Violations of conservation regulations	Number of incidents	Reports from Cu Lao Cham Management Board and commune authority	Continuous recording, summarised every six months	Decreasing over time; ≤2 incidents/6 months in key restoration zones	Cu Lao Cham Management Board
Patrol and monitoring frequency	Times/month	Activity logbook	Monthly	≥4 times/month during peak tourist season; ≥2 times/month in off-season	Cu Lao Cham Management Board
Community/visitor compliance with conservation regulations	%	Number of compliant observations/total observations × 100	Twice per year, covering peak and off-season periods	≥70%	Local stakeholder consultation
Governance effectiveness score ***	Score (0–10)	Structured assessment of 5 criteria by experts and stakeholders	Annually	≥7	[21,30] and expert judgement

Note: * Transect width extends from the water's edge to the highest tide boundary. ** Trampling damage score: 1 = no visible impact; 2 = a few broken or crushed leaves; 3 = small patches of trampled seagrass forming faint traces; 4 = clearly visible footpaths through the seagrass bed; 5 = widespread destruction of the seagrass bed with disturbed sediment. *** Governance effectiveness was assessed across five criteria: role clarity, patrol and monitoring, enforcement, stakeholder coordination, and use of monitoring data in decision-making. Each criterion was scored from 0 to 2 (0 = ineffective, 1 = partial, 2 = effective), giving a total score of 0–10. Expert and community scores were averaged.

Targets for this group were derived from multiple reference sources. Vessel activity and visitor density were set relative to the baseline. Waste-reduction targets followed project objectives and existing technical guidance. The remaining indicators—trampling, violations, patrol activity, compliance, and governance effectiveness—were calibrated using Management Board records, expert judgement, stakeholder feedback, and a practical assessment of local enforcement capacity. Vietnamese regulations do not yet establish specific thresholds for these management- and tourism-related indicators; consequently, the proposed values serve as locally grounded benchmarks that should be revisited and adjusted over time rather than treated as fixed standards. Ultimately, this pressure-response pairing enables the framework to diagnose the root causes of underperformance, whether they stem from unchecked pressures, weak compliance, lax enforcement, or insufficient governance capacity.

3.1.5. Learning, Adaptation, and Knowledge Management Indicator Group

The learning, adaptation, and knowledge dimension includes six indicators that examine the extent to which monitoring results, implementation experience, and stakeholder feedback are converted into practical management adjustments. As presented in Table 5, these indicators cover documented lessons, management or technical adjustments, locally adapted restoration proposals, improvements in conservation knowledge, perceived scalability potential, and stakeholder satisfaction with interdisciplinary collaboration.

Table 5. Core indicators and proposed targets for the Learning, Adaptation, and Knowledge Management Indicator Group.

Indicator	Unit	Measurement Method	Frequency	Proposed Target	Reference/Target Basis
Lessons learned documented	Count	Internal review meeting minutes, field reports, and consultation records	Annually	≥4 lessons/year	[11] and Cu Lao Cham Management Board
Management or technical adjustments made based on lessons learned	Count	Cross-check between original workplan, revised plan, and implementation records	Annually	≥2 adjustments/year	[11] and Cu Lao Cham Management Board
Locally adapted restoration proposals developed	Count	Records from expert consultation, community workshops, and technical review meetings	Annually	≥3 proposals/year, with ≥1 proposal implemented	[11] and expert judgement
Improvement in conservation knowledge after training	%	Pre- and post-training survey	After each training session	≥70% of participants show improvement	[21] and local stakeholder consultation
Scalability potential of the restoration model	Score (1–5)	Likert assessment by expert panel using a 1–5 scale	Annually	≥4/5	[9,11] and expert judgement
Stakeholder satisfaction with interdisciplinary collaboration	Mean score (1–5)	Stakeholder survey	Annually	≥4/5	[10,11] and local stakeholder consultation

Note: The proposed targets are site-specific adaptive management targets and were developed based on MEL principles, Management Board documentation, project learning records, expert judgement, stakeholder feedback, and the adaptive management needs of Cu Lao Cham.

Expert and stakeholder consultations highlighted several key learning processes, including documenting field experience, revising technical and management approaches, sharing knowledge across institutions and communities, and adapting restoration measures to local conditions. Taken together, these indicators ensure that monitoring functions as a continuous feedback loop for adaptive management.

The proposed targets were developed as site-specific adaptive-management benchmarks, drawing on MEL principles, project records, Management Board documentation, and expert judgement. For count-based indicators, such as documented lessons, management adjustments, and locally adapted proposals, emphasis should not be placed solely on numerical counts. Instead, these indicators should be interpreted in terms of whether the recorded lessons and adjustments were actually applied in management decisions and field practices.

Improvements in conservation knowledge and stakeholder satisfaction were gauged through training and consultation outcomes, while scalability potential relied on expert judgement. Because no national technical standards currently exist for learning, collaboration, or adaptive-management performance, these targets will require refinement as implementation cycles progress. Ultimately, this group prevents monitoring from becoming

a mere reporting exercise by providing the critical feedback loop through which restoration practices can continuously improve.

3.2. Weights of Indicator Groups

All individual expert pairwise-comparison matrices met the consistency requirement (CR = 0.051–0.089). Experts and stakeholders both recognised the importance of biological recovery but differed in their relative priorities. Experts ranked Biological–Ecological indicators highest (0.38), followed by Community Livelihoods and Social Well-being (0.26) and Habitat Quality and Environmental Stress (0.22; Table 6). Stakeholders, in contrast, prioritised Community Livelihoods and Social Well-being (0.31), followed closely by Biological–Ecological indicators (0.25) and Anthropogenic Pressures and Management (0.20).

Table 6. Integrated weights of indicator groups.

Indicator Group	Expert-Derived Weight	Stakeholder-Derived Weight	Integrated Group Weight (70:30)	Interpretation
Biological–Ecological	0.38	0.25	0.34	Core group, directly reflecting seagrass bed recovery
Habitat Quality and Environmental Stress	0.22	0.16	0.20	Ensures suitable habitat conditions for recovery
Community Livelihoods and Social Well-being	0.26	0.31	0.28	Highly prioritised by stakeholders; linked to livelihood benefits and social equity
Anthropogenic Pressures and Management	0.10	0.20	0.13	Reflects pressure control and management effectiveness
Learning, Adaptation, and Knowledge Management	0.04	0.08	0.05	Provides an enabling feedback function for adaptation and replication
Total	1.00	1.00	1.00	

After combining the expert- and stakeholder-derived weights using the 70:30 ratio, the Biological–Ecological group received the highest overall weight (0.34). This was followed by Community Livelihoods and Social Well-being (0.28), Habitat Quality and Environmental Stress (0.20), Anthropogenic Pressures and Management (0.13), and Learning, Adaptation, and Knowledge Management (0.05).

While ecological recovery emerged as the primary criterion, the weighting pattern also reflects critical management realities. The substantial weight assigned to community livelihoods and anthropogenic pressures—dimensions strongly emphasised by stakeholders—indicates that biophysical gains are unlikely to be sustained without community acceptance and effective enforcement. Thus, while ecology remains the central focus, the local social and institutional context is inherently integrated into the assessment rather than treated as an afterthought.

Given that the 70:30 expert-to-stakeholder ratio was a context-specific methodological choice, a sensitivity analysis was performed to assess the robustness of the prioritisation under different weighting assumptions. Table 7 presents the integrated weights under four expert-to-stakeholder weighting scenarios, including the 70:30 base-case scenario and three alternative scenarios: 50:50, 60:40, and 80:20.

Table 7. Sensitivity analysis of integrated indicator-group weights under the 70:30 base-case and alternative expert-to-stakeholder ratios.

Expert: Stakeholder Ratio	Biological–Ecological	Habitat Quality and Environmental Stress	Community Livelihoods and Social Well-Being	Anthropogenic Pressures and Management	Learning, Adaptation, and Knowledge Management
50:50	0.315	0.190	0.285	0.150	0.060
60:40	0.328	0.196	0.280	0.140	0.056
70:30	0.341	0.202	0.275	0.130	0.052
80:20	0.354	0.208	0.270	0.120	0.048

Note: Values are reported to three decimal places to show changes across sensitivity scenarios.

The sensitivity analysis confirmed that the rank order of the five indicator groups remained stable across all four expert-to-stakeholder weighting scenarios. Biological–Ecological indicators consistently ranked first, followed by Community Livelihoods and Social Well-being, Habitat Quality and Environmental Stress, Anthropogenic Pressures and Management, and Learning, Adaptation, and Knowledge Management.

Increasing the expert weight slightly elevated the Biological–Ecological score, while correspondingly reducing the emphasis on Community Livelihoods and Anthropogenic Pressures. This aligns with the stronger relative importance stakeholders initially placed on livelihood and management dimensions. However, these shifts were minor and did not alter the overall rank order. The final prioritisation is therefore robust and not overly sensitive to the chosen 70:30 integration ratio.

4. Proposed Application and Operational Integration of the Framework

The practical application of the framework is guided by the operational matrix (Supplementary Material S1), which directs the Management Board and technical partners on exactly what data to collect, who is responsible, how often to monitor, and how to adjust management interventions when ecological or social targets are not met.

The composite scoring procedure is intended for use in future monitoring cycles, once sufficiently complete and comparable data have been collected across the five indicator groups. In practical terms, it should be integrated with the Management Board's existing biodiversity and environmental monitoring activities, while adding a restoration-specific layer of indicators and scoring procedures for seagrass recovery. Its application would involve a repeated cycle of establishing baselines, collecting and verifying monitoring data, calculating group and overall scores, reviewing the results, and adjusting management actions where necessary.

Baseline conditions should first be established for indicators that are strongly shaped by local ecological, social, or management contexts. Indicators linked to national standards or fixed project targets can be assessed directly against those thresholds. For indicators without such thresholds, performance should be evaluated by tracking changes across successive monitoring periods. Slow-response indicators, such as species composition or below-ground biomass, should be interpreted over several monitoring cycles rather than judged solely by short-term target achievement. In these cases, the direction of change and the surrounding environmental conditions may be more informative than whether a target is met in a single assessment period. Data collection should follow the methods and monitoring frequencies presented in Tables 1–5.

To distinguish restoration-related changes from natural environmental variability—such as seasonal fluctuations, storm disturbances, or broader background changes—future implementation of the framework should adopt a Before–After–Control–Impact (BACI)

design or an equivalent comparative approach wherever feasible. Specifically, restored plots should be monitored before and after intervention and compared concurrently with suitable non-restored control sites and/or undisturbed natural reference meadows. The selection of these comparison sites should account for ecological similarity, exposure, depth, substrate type, and pre-intervention seagrass condition to ensure valid attribution of observed changes to restoration actions rather than confounding environmental factors.

The Cu Lao Cham Nature Reserve Management Board would play the central role in compiling and initially verifying the monitoring data, with support from technical agencies, local authorities, research institutions, community groups, and tourism stakeholders. Ecological and environmental indicators would be based mainly on field surveys and laboratory analyses, while indicators related to livelihoods, management, compliance, and learning would draw on household surveys, administrative records, training evaluations, and stakeholder consultations.

Practical implementation should follow a tiered and adaptive monitoring approach that leverages existing institutional capacities. Core indicators that are relatively feasible to measure and directly relevant to restoration performance and management decisions should receive priority in routine monitoring and be primarily assigned to the Management Board, whereas resource-intensive or slow-response indicators requiring specialised laboratory or GIS analysis can be delegated to technical partners and assessed less frequently. The frequencies specified in Tables 1–5 should be regarded as minimum schedules and may be increased following storms, pollution events, unusual turbidity, or peak tourism pressure. Data quality should be supported through standardised field protocols, instrument calibration, replicate measurements where appropriate, laboratory quality checks, and cross-checking of administrative and observational records.

For each indicator, performance would be assessed by comparing observed values with the proposed targets. These results would then be aggregated at the group level and combined with the integrated weights to calculate contribution scores for each indicator group, leading to an overall restoration-effectiveness score. Missing data should be clearly reported rather than treated automatically as non-achievement. A full composite score should only be calculated when data coverage is sufficient across all five dimensions; therefore, a minimum acceptable data-coverage threshold should be established and validated during pilot implementation before the composite score is used for formal decision-making.

Assessment results should be reviewed jointly by the Management Board, relevant authorities, technical partners, and stakeholder representatives. This review must not focus exclusively on the overall composite score, as aggregation can obscure important weaknesses within individual indicator groups or specific indicators. Where weak performance is identified, the results should be explicitly linked to targeted management responses, such as refining restoration techniques, strengthening pollution control, improving visitor management, or revising monitoring methods, depending on the underlying problem.

Finally, the framework should be revisited periodically as monitoring data and field experience accumulate. Indicator definitions, targets, measurement methods, and weights may need adjustment over time to reflect changing environmental conditions, institutional capacity, and lessons learned. To be genuinely useful, the framework must be embedded within the Management Board's routine monitoring, reporting, and adaptive management processes, rather than treated as a separate, standalone assessment exercise. Ultimately, the long-term value of the framework depends on whether monitoring results are consistently used to inform adaptive management decisions over successive cycles.

5. Discussion

Seagrass restoration is understood here not only as a process of biological recovery, but also as a broader social–ecological process shaped by habitat conditions, community livelihoods, and management effectiveness. The five indicator groups reflect this perspective by extending ecological monitoring to include human pressures and adaptive learning, thereby moving beyond the narrower scope of conventional restoration monitoring.

Ecological metrics remain essential for tracking meadow recovery [2,4,5]. However, they capture only part of the restoration process. On their own, they provide limited insight into whether recovery is being supported by suitable environmental conditions, reduced human pressures, community support, or effective management. This framework addresses that gap by bringing ecological and social–institutional dimensions into a single assessment structure [6–8].

Integrating DPSIR and MEL is necessary to overcome their individual limitations: DPSIR alone risks becoming a static diagnostic checklist, while MEL typically measures progress without diagnosing root causes. Combining them closes the management loop by actively tracing observed outcomes back to specific drivers and pressures to trigger targeted responses. Consequently, the framework moves beyond a static indicator list to provide a dynamic, diagnostic basis for adaptive management. The weighting and aggregation procedures follow established composite-indicator practices [22], ensuring the assessment remains transparent and interpretable.

Compared with earlier approaches, the proposed framework addresses three key limitations. Conventional DPSIR applications in coastal and marine contexts provide effective causal diagnosis but often remain static checklists lacking iterative feedback loops for adaptive management. Conversely, MEL-based frameworks widely used in conservation [11] link monitoring to learning but typically do not trace outcomes back to their underlying drivers, limiting their diagnostic power. Previous seagrass monitoring efforts have also focused predominantly on ecological indicators [2,4,5], with limited integration of social, governance, and learning dimensions. By combining DPSIR's causal structure with MEL's feedback cycle and incorporating weighted composite scoring, the proposed framework moves beyond both static diagnosis and unstructured monitoring.

Regarding prioritisation, the weighting results indicate a broad consensus that ecological recovery should remain the main focus of restoration assessment, although experts and stakeholders placed different levels of emphasis on several dimensions. Experts assigned greater importance to Biological–Ecological indicators (0.38), whereas stakeholders gave relatively higher priority to Community Livelihoods and Social Well-being (0.31), as well as to Anthropogenic Pressures and Management. The final 70:30 integrated weights preserve the ecological focus of the assessment while still recognising the social and governance conditions that influence whether restoration outcomes can be sustained over time.

The relatively low numerical weight assigned to the Learning, Adaptation, and Knowledge Management group should not be interpreted as meaning that learning is unimportant. In this framework, learning functions mainly as a feedback mechanism, helping translate monitoring results into management adjustments. Its contribution is therefore not fully captured by a composite score that is structured around more direct ecological, social, and pressure-related outcomes. These weights should be understood as context-specific and should be revisited as additional monitoring evidence becomes available.

Furthermore, the Learning, Adaptation, and Knowledge Management indicators ensure that unexpected environmental disturbances (e.g., severe storms, monsoonal fluctuations, or pollution events) trigger formal management adjustments and contextualised interpretation, rather than being misinterpreted solely as a failure of the restoration effort.

The framework was shaped for Cu Lao Cham using baseline data, national regulations, expert input, and stakeholder consultation. That said, not every target rests on equally solid evidence—some lean more on project objectives than on robust empirical data, and those will need recalibrating as monitoring moves forward.

In this framework, the "initial project baseline" refers to the average conditions recorded in the restoration area before any restoration activities were implemented. Assessment is therefore based on changes relative to this starting point, while also considering natural factors that may influence indicator values independently of restoration actions, such as seasonal variation, typhoons and monsoonal storms, and broader background fluctuations in environmental conditions. The persistence of a low seagrass extent from 2017 to 2025 indicates that the restoration initiative is being implemented within a substantially degraded system, and future outcomes should be interpreted against both the historical trajectory and contemporary pressures.

The composite score works as a screening tool, intended to flag trends and direct management attention; it is not a definitive judgement on whether restoration has succeeded. It should therefore never be interpreted on its own. Group- and indicator-level results should be considered alongside the composite score, since a single aggregated number can obscure important ecological or social weaknesses [22].

A further methodological consideration is the implicit equal weighting of indicators within each group. While certain indicators hold greater ecological importance—for example, meadow area and species composition represent fundamental recovery in the Biological–Ecological group, whereas mean leaf length is a secondary metric—assigning specific intra-group weights would complicate the consultation process. Equal weighting was therefore retained to maintain transparency and avoid over-parameterisation. To prevent critical failures from being masked, the framework mandates that the composite score must always be interpreted alongside indicator-level results.

Although the MEL–DPSIR framework was developed specifically for Cu Lao Cham, some components may provide a general structure for adaptation to other seagrass restoration projects. The overarching MEL–DPSIR logic and the multidimensional assessment approach can be transferred in principle, while the weighting and composite-scoring procedures may also be reused or replaced by alternative methods depending on the decision context. In contrast, the specific indicators, numerical targets, monitoring frequencies, data sources, institutional responsibilities, and expert–stakeholder weighting ratio require site-specific calibration. Such adaptation should reflect local ecological baselines, dominant pressures, regulatory standards, governance arrangements, stakeholder priorities, and available monitoring capacity. The Cu Lao Cham framework should therefore be viewed as an adaptable template rather than a directly transferable standard.

Several limitations should be acknowledged. First, as complete monitoring data are unavailable, this study demonstrates framework development rather than empirical validation. Second, target evidentiary strength varies; regulatory thresholds are established, whereas project-specific targets remain provisional and require recalibration. Third, the 70:30 expert–stakeholder ratio is a context-specific working assumption rather than an empirically validated standard; thus, future studies may employ formal consensus methods like Delphi. Fourth, the partially compensatory aggregation and equal intra-group weighting mean the composite score must be interpreted alongside indicator-level results to avoid masking specific weaknesses. Fifth, some qualitative indicators involve subjectivity, and ecological time-lags may delay the detection of measurable changes in below-ground biomass or species composition. Sixth, although the framework now recommends a BACI or equivalent comparative design for future implementation, such a design was not empirically applied in this preliminary study. Attribution of observed ecological or social

changes specifically to restoration interventions—rather than to natural variability or external pressures—will therefore require rigorous before–after monitoring of both restored and suitable comparison sites in subsequent assessment cycles. Finally, although the framework includes operational safeguards for resource constraints, data quality, and missing observations, its long-term feasibility will depend on stable financing, sustained institutional capacity, and the integration of monitoring activities into the Management Board's regular work programme.

Going forward, the priority is repeated monitoring cycles, careful validation of data, and better documentation of how results actually feed into management decisions. None of these limitations erase what the framework does offer: a practical, locally grounded starting point for monitoring and adaptive management in Cu Lao Cham—one flexible enough, with the right local adjustments, to be adapted for other seagrass restoration sites too.

6. Conclusions

This study developed a preliminary MEL–DPSIR framework comprising 31 indicators across five multidimensional groups to evaluate seagrass restoration at Cu Lao Cham Nature Reserve as a social–ecological process. The weighting results demonstrated that biological recovery remains the central priority, but its long-term sustainability also depends on livelihood benefits, habitat quality, pressure management, and adaptive learning. By integrating expert judgement with stakeholder perspectives, the framework provides a structured translation of broad international guidance into a locally grounded framework designed to support operational decision-making.

By explicitly linking causal drivers to measurable feedback loops and providing an operational matrix that specifies data sources, responsibilities, and management triggers, the framework is structurally designed to support adaptive management. It enables managers to systematically identify performance gaps and adjust interventions as soon as routine monitoring data become available, even before full empirical validation is achieved.

Because the restoration project is in its early stages and complete monitoring data are unavailable, this study demonstrates framework development rather than empirical validation. Future work must therefore focus on piloting the framework through repeated monitoring cycles, refining targets as evidence accumulates, and testing its ability to distinguish restoration effects from natural variability. Ultimately, the framework's real-world value will depend on stable financing, sustained institutional capacity, and its formal integration into the Management Board's routine adaptive management processes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/coasts6030039/s1, Supplementary Material S1: Operational MEL–DPSIR matrix linking the 31 indicators to data sources, responsibilities, monitoring frequencies, and management responses; Supplementary Material S2: FAHP weighting summary, expert–stakeholder integration, and consistency checks.

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Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The data supporting the indicator framework, including indicator definitions, scoring criteria, weighting templates, and consultation forms, are available from the corresponding author upon reasonable request. No large public dataset was generated in this study. Some project baseline data are subject to permission from WWF-Vietnam and the Cu Lao Cham Nature Reserve Management Board and are available upon reasonable request with appropriate authorisation.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
BACI	Before–After–Control–Impact
CR	Consistency Ratio
DO	Dissolved oxygen
DPSIR	Drivers–Pressures–State–Impact–Response
DW	Dry weight
GCBC	Global Centre on Biodiversity for Climate
GIS	Geographic information system
GPS	Global positioning system
LOI	Loss on Ignition
MEL	Monitoring, Evaluation, and Learning
MPA	Marine protected area
QCVN	National Technical Regulation
TFN	Triangular Fuzzy Number
TSS	Total suspended solids
WWF	World Wide Fund for Nature

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