Marjal dels Moros: a model site for the structural, functional, and socioeconomic assessment of managed Mediterranean marshes

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Abstract

Coastal wetlands deliver critical ecosystem services but remain highly degraded by anthropogenic and climatic pressures. This study presents an integrated structural, functional, and socio-economic assessment of Marjal dels Moros, a managed Mediterranean brackish marsh in eastern Spain, to evaluate restoration effectiveness and inform climate-based management. Six subsites representing well-preserved, altered, and restored conditions were analyzed for water and sediment properties, microbial community composition, and greenhouse gas (GHG) fluxes, alongside a multi-criteria socio-economic evaluation of restoration scenarios. Results revealed strong environmental heterogeneity mostly driven by the hydroperiod and salinity gradients, with restored sites exhibiting intermediate sediment characteristics and reduced proxies of pathogenic bacterial genera. Microbial ordination highlighted hydrological control of methane-cycling guilds, while GHG fluxes showed a clear functional gradient: as such, permanently inundated, nutrient-rich sites emitted high CO_2 and CH_4 fluxes whereas subsites with seasonal drying and higher salinity acted as near-neutral or CH_4-suppressing zones. These patterns confirm that hydroperiod and salinity management shape microbial guilds and carbon dynamics, directly influencing climate regulation services. Socio-economic analysis indicated stakeholder preference for measures enhancing natural hydrology, habitat diversity, and risk reduction, supporting restoration strategies. Findings underscore hydrology-first strategies, integrated monitoring of functional indicators, and inclusive governance as key to achieving ecological integrity, climate mitigation, and socio-economic co-benefits. The proposed framework offers transferable guidance for policy-relevant restoration of Mediterranean coastal wetlands under multi-use pressures.

Keywords Coastal wetlands; Mediterranean marshes; ecological restoration; greenhouse gas (GHG) fluxes; microbial communities; ecosystem services; adaptive management; socio-economic assessment; hydrology; climate-smart strategies.

1. Introduction

Coastal wetlands are priority ecosystems for environmental management due to their capacity to deliver multiple ecosystem services (Barbier, 2019) while being highly exposed to anthropogenic and climatic pressures (Newton et al., 2020). They play a key role in biodiversity conservation, hydrological regulation, nutrient retention, and carbon storage, contributing simultaneously to climate change mitigation and adaptation (Nicholls & Lowe, 2004; Morris, et al., 2012; Wigand et al., 2017; Hagger et al., 2022). These functions are increasingly recognized in international and regional policy frameworks, including the Ramsar Convention, the EU Biodiversity Strategy for 2030, and climate-neutrality targets, which emphasize the protection and restoration of wetlands as nature-based solutions (Thorslund et al., 2017; Ferreira et al., 2023).

Despite their recognized value, coastal wetlands remain among the most degraded ecosystems worldwide (Li et al., 2018; Newton et al., 2020). Land-use change, hydrological modification, pollution, and habitat fragmentation have led to widespread losses in ecological integrity, status and ecosystem service provision (Newton et al., 2020; Morant et al., 2021). Climate change further exacerbates these pressures through sea-level rise, altered precipitation regimes, and increased frequency of extreme events (Day et al., 2008). In response, environmental managers are increasingly required to implement adaptive, evidence-based strategies that balance conservation objectives with human uses, while aligning with regulatory instruments such as the EU Water Framework Directive (WFD) and the Habitats Directive (HD) (Verhoeven, 2014).

Mediterranean brackish marshes constitute a distinctive type of coastal wetland shaped by strong seasonal variability, complex freshwater–marine interactions, and limited tidal influence (Morant et al., 2020). Their ecological structure and functioning are closely regulated by water management practices, salinity gradients, and sediment processes, making them particularly sensitive to both climatic variability and human intervention (Ibñez et al., 2000). These characteristics place Mediterranean marshes at the intersection of multiple policy domains, including water management (WFD) (Pérez-Ruzafa et al., 2011), nature conservation (Natura 2000 network, HD) (De Wit & Boutin, 2023), flood risk management (Estrela-Segrelles et al., 2021), and climate adaptation strategies (Losada et al., 2019). These particular coastal marshes, besides, are explicitly referenced in European policy agendas, which promote the integration of their proper structural and functioning into planning and decision-making (e.g. RD817/2015 in Spain). However, the multifunctionality of these systems also creates trade-offs, particularly in densely populated coastal zones where urban, industrial, and agricultural demands compete with conservation objectives (Novoa et al., 2020).

Historically, Mediterranean coastal marshes like Marjal dels Moros (València, Spain) have been extensively modified through drainage, reclamation, agricultural intensification, and urban and industrial expansion (Perennou et al., 2020). Hydrological alterations—often designed to control flooding or maximize land productivity—have disrupted natural water regimes, altered salinity patterns, and reduced habitat heterogeneity (Rochera et al., 2025). These changes have led to declines in biodiversity, modifications of biogeochemical cycles, and, in some cases, increased greenhouse gas (GHG) emissions, undermining both conservation and climate-related objectives (Morant et al., 2020).

In recent decades, restoration and management initiatives have increasingly focused on re-establishing hydrological functionality, improving water quality, and enhancing habitat diversity, in line with the WFD's ecological status objectives and the HD conservation targets (Verhoeven, 2014; Filipe et al., 2019; Stefanidis et al., 2021). More recently, climate policies have highlighted the role of wetlands in carbon sequestration and emissions reduction, reinforcing the need to consider ecosystem functioning alongside traditional structural indicators (Seddon et al., 2020, 2021). Nevertheless, evaluating the effectiveness of restoration measures remains challenging, particularly where outcomes are influenced by external pressures such as surrounding land use, industrial activities, or changes in regional water governance.

A persistent limitation in wetland management is the lack of integrated assessments that link environmental structure, ecosystem functioning, and ecosystem services in a way that directly informs management planning and policy implementation. Many studies focus on individual components, such as water quality, vegetation, or biodiversity, without explicitly connecting them to functional processes or management objectives defined in official plans.

For managed wetlands embedded in complex socio-environmental landscapes, there is a clear need for applied frameworks that integrate structural indicators (water and sediment properties), functional processes (GHG fluxes and biological activity), and socioeconomic dimensions (ecosystem services, public use, governance). Such approaches are essential to evaluate whether restoration actions contribute effectively to policy objectives, including ecological status improvement, climate resilience, and sustainable use.

This study presents an integrated structural, functional, and socioeconomic assessment of the Marjal dels Moros coastal marsh (eastern Spain) as a model site for the environmental management of Mediterranean brackish wetlands. The site is designated under conservation frameworks and has been the focus of multiple restoration initiatives, while simultaneously being exposed to significant external pressures, including urban and industrial development. This combination makes it particularly suitable for evaluating management effectiveness in a policy-relevant context.

Building on the need for integrated evaluations, this study aims to: (i) characterize environmental heterogeneity across six representative subsites of Marjal dels Moros, focusing on water and sediment properties that underpin ecological integrity and microbial community composition; (ii) assess functional processes through sediment greenhouse gas fluxes, identifying hydrological and trophic drivers of carbon dynamics; and (iii) analyse socio-economic performance and stakeholder priorities to determine how restoration scenarios influence ecosystem service provision, governance, and financing. By linking structural, functional, and socio-economic dimensions, we seek to provide actionable evidence for adaptive management and policy implementation under European frameworks, emphasizing hydrology-centred strategies and integrated monitoring as mechanisms to enhance resilience and climate-smart outcomes in Mediterranean coastal wetlands.

2. Materials and Methods

2.1. Study site

The Marjal dels Moros, **Fig. 1**, (39.61579°N to 39.64107°N, -0.27997°E to -0.240362°E) is a Mediterranean brackish coastal wetland (6 km²; 619.44 ha protected) located between the municipalities of Puçol and Sagunt (València, Spain). It is designated as Natura 2000 (SAC/SPA; code ES0000148) and hosts eight habitat types, including brackish marshes and humid dune slacks. It is classified in EUNIS level 2 as Coastal saltmarsh and saline reedbed (A2-5). Land cover is dominated by marshes and abandoned crops. Principal pressures include hydrological alteration and water scarcity (groundwater over-exploitation). Hydrologically, the system depends on a mosaic of inflows/outflows and engineered controls. This has been historically mitigated by wastewater and irrigation return flows that, as freshwater inputs often high in nutrients, have compromised the natural salinity regime required by the salt marshes. Other threat is coastal erosion associated with the nearby Sagunt Port, urban and industrial expansion (Parc Sagunt), and recurrent fire risk. Management is led by the Generalitat Valenciana, with public use, environmental education (CEACV), and light agro-pastoral activities allowed in designated zones.

Socio-economically, the wetland sits within a dynamic territory marked by industrial growth (car-battery gigafactory, port expansion), seasonal tourism/recreation (birdwatching, education), and constrained water resources. Annual visitation to CEACV was ~10,000 users in 2024. Restoration governance involves regional authorities, academia, NGOs, and local councils, with financing historically combining public funds (e.g., LIFE projects) and municipal commitments, while long-term maintenance funding remains fragile.

Six subsites were chosen to represent a gradient of hydrological and salinity conditions across three conservation categories: well-preserved, altered, and restored (two per category). Sampling was carried out in Spring 2024. Altered subsites remain artificially flooded for extended periods due to external water inputs, losing the seasonal hydroperiod and brackish character. Restored subsites exhibit partial recovery of flooding and salinity patterns approaching natural dynamics. Well-preserved subsites maintain semi-temporary hydrology with groundwater inputs and seasonal desiccation. This framework enables assessment of how salinity and hydroperiod influence ecosystem structure, function, and service provision.

Altered subsites: These marsh areas have undergone severe hydrological, trophic, and morphological disturbances. Alterations include drainage, groundwater extraction, and artificial water supply from irrigation and wastewater sources, leading to partial desalinization. Nutrient enrichment from agricultural runoff, domestic effluents, and industrial discharges has caused eutrophication and organic enrichment. Morphological changes due to land-use conversion and soil degradation have resulted in habitat loss, reduced native vegetation, proliferation of invasive species, and disruption of natural salinity gradients. Historically, agricultural exploitation and hunting further degraded vegetation structure and ecosystem services.

Restored subsites: Restoration combined active and passive measures aimed at soil, hydrology, and vegetation recovery. Actions included substrate reconstruction, topographic adjustments to restore elevation and hydrological connectivity, and active planting of native species. Hydrological improvements involved diversifying water sources (reuse of irrigation surpluses, controlled groundwater inputs) and maintaining seasonal flooding even in dry years. Vegetation recovery was achieved through planting and passive recolonization following pressure reduction. Since renaturalization, four Flora Microreserves (1999–2003) and two Fauna Microreserves (2004–2006) have been established. Regular mowing of helophytic vegetation is implemented as a management measure.

Well-Preserved subsites: These sites represent intact brackish marsh habitats with stable hydrological connectivity, including natural groundwater intrusion and seasonal drying. Water quality remains high, and structural alterations are minimal. Vegetation consists of halophytic communities adapted to variable salinity regimes typical of Mediterranean coastal marshes, including reed beds, bulrush stands, and halophytic shrubs. Native biodiversity and ecological functions are largely maintained.

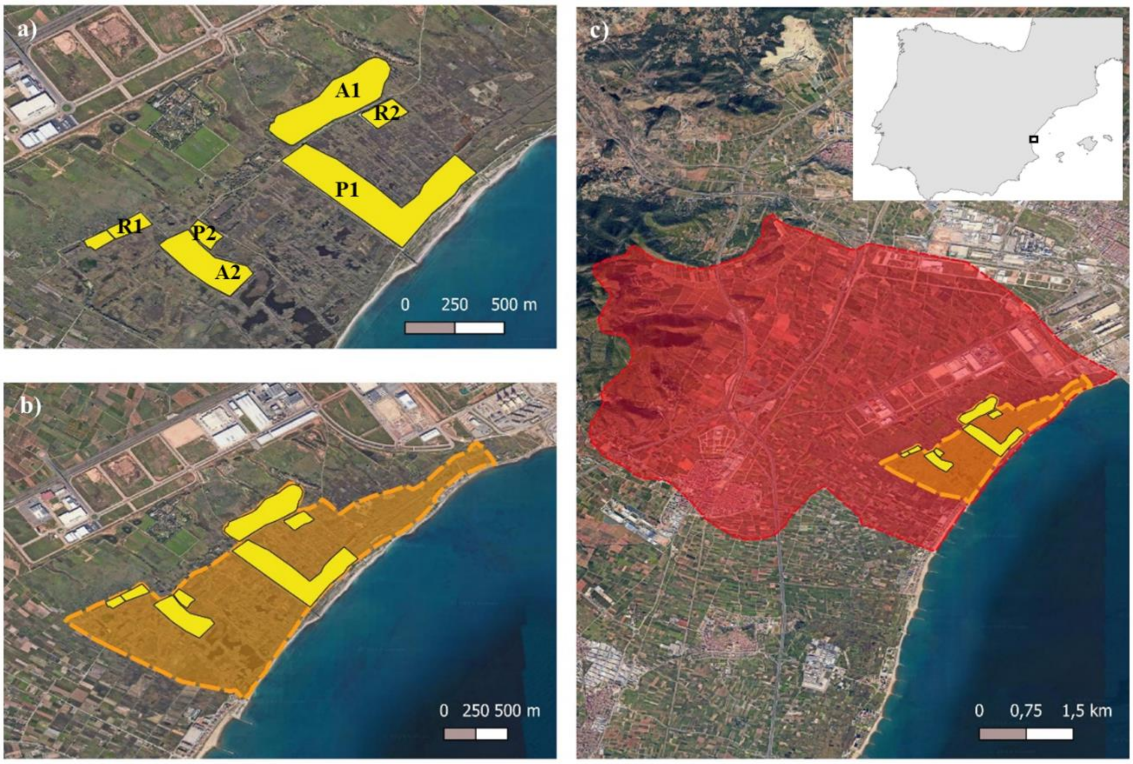

Figure 1. Marjal dels Moros subsites (R: restored, A: altered and P: well-preserved), protected site and subcatchment area.

2.2. Environmental characterization

Physicochemical and trophic characterization of the water and sediment was conducted adhering to the standardized methodologies of the RESTORE4Cs project (Oliveira et al., under review). Water column analysis included *in situ* recording of depth, temperature, dissolved oxygen (DO), and conductivity. Furthermore, samples were processed to quantify alkalinity, microbial standing stocks (bacterial biomass and Chlorophyll-a), and key nutrient fractions, specifically orthophosphate (PO_4), ammonium (NH_4), nitrate/nitrite (NO_x), Total Nitrogen (TN), and Total Phosphorus (TP). Sediment assessment (Misteli et al., under review) focused on structural and organic properties, including moisture content, ash-free dry mass, Total Organic Carbon (TOC), and total nutrient concentrations (Total-N, Total-P).

2.3. Structural analysis (bacterial communities)

In this study, a total of 28 sediment samples were analysed to characterize archaeal and bacterial communities. Genomic DNA was extracted from approximately 300–500 mg of sediment per sample using the EZNA Soil DNA isolation kit (Omega Bio-Tek, Inc.), following the protocol described by Picazo et al. (2019). The V4 hypervariable region of the 16S rRNA gene was targeted using primers 515f/806r. Amplicon libraries were prepared according to Kozich James et al. (2013), normalized using Invitrogen SequalPrep plates, and sequenced on an Illumina MiSeq platform (2x250 bp paired-end) using a v2 500-cycle reagent cartridge. Bioinformatic processing was conducted using the UPARSE pipeline within USEARCH v12b (Edgar, 2013). After merging paired-end reads and filtering for a maximum expected error rate of 0.5%, chimeric sequences were removed using UCHIME. The remaining sequences were denoised via the unoise3 algorithm (Edgar, 2016) and clustered into Zero-radius Operational Taxonomic Units (ZOTUs) at 100% identity. Taxonomic assignment was performed using SINA v1.2.1152 against the SILVA 138.1 database with a minimum identity threshold of 0.8 (LCA method). Non-target sequences (mitochondria, chloroplasts) and those with low alignment quality (<90%) were discarded. Finally, to normalize sequencing depth, the ZOTU table was rarefied 100 times, and the average counts were used for downstream statistical analysis.

2.4. Statistical analyses

To evaluate spatial and temporal patterns in microbial community structure and their relationship with environmental gradients, Principal Coordinates Analysis (PCoA) was performed using the PRIMER 7 software package. Prior to analysis, ZOTU abundance tables were square-root transformed and standardized to totals to downweight highly abundant taxa (Legendre & Gallagher, 2001), and resemblance matrices were calculated based on Bray-Curtis dissimilarity. A separate PCoA was conducted for environmental variables using a square-root transformed and normalized data matrix.

2.5. Functional analysis (GHG emissions)

At each subsite, six intact sediment cores were collected seasonally manually using transparent methacrylate tubes (50–100 cm length, 4 cm diameter). Each core included approximately 15 cm of sediment and an overlying water column corresponding to in situ depth. Immediately after extraction, cores were sealed, leaving a headspace of at least 10 cm to enable gas measurements.

Cores were transported intact to the laboratory and air-purged to remove accumulated gases. During purging, cores were gently agitated without disturbing sediment structure to facilitate bubble release. An initial headspace sample was collected using a syringe with a three-way valve through a rubber septum, transferring 20 mL of air into pre-evacuated 12 mL gas-tight glass exetainers. Atmospheric pressure and temperature were recorded. After sampling, cores were resealed and incubated for ~24 h in bioclimatic chambers under temperature and light conditions approximating field conditions.

At the end of incubation, headspace concentrations of CO_2 and CH_4 were measured. Potential fluxes were calculated as the difference between final and initial concentrations over the incubation period. To account for ebullition, cores were vigorously shaken post-incubation to release trapped gases, and an additional headspace sample was taken.

Gas fluxes were computed from concentration changes using the ideal gas law and normalized to surface area:

$$F_{\text{gas}} = \frac{dp_{\text{gas}}}{dt} \cdot \frac{V}{RTS}$$

where F_{gas} is expressed in mmol m^{-2} day^{-1}, $\frac{dp_{\text{gas}}}{dt}$ is the rate of change in gas partial pressure (µatm s^{-1}), $V$is chamber volume (m^3), R is the ideal gas constant (L atm K^{-1} mol^{-1}), $T$is air temperature (K), and $S$is chamber surface area (m^2).

2.6. Socioeconomic analysis

A multi-criteria analysis (MCA) was applied to evaluate socio-economic trade-offs of restoration alternatives, integrating indicators tied to management objectives and stakeholder preferences. The approach comprised: (i) indicator definition and data collation; (ii) stakeholder weighting; and (iii) scenario scoring with multiple normalization methods to test robustness. A detailed description of the method used, and the definitions of each indicator is in **Supplementary Material**, and in Anglada et al. (2025).

Indicators were selected through co-design (University of Valencia, Vertigo Lab, MedWet, managing authority) and derived from monitoring programs and official datasets. We retained indicators with direct management relevance and reliable data availability:

- **Socio-economic activities:** *Agriculture* (Corine-Land Cover 2018; tailored perimeter), *Industrial activities* (presence/interaction near the wetland), *Tourism/recreation* (CEACV users), *Water provisioning* (hydroperiod months).
- **Employment and costs:** *Jobs created/lost* (current staff: 6 permanent + 7 temporary; planned temporary jobs per option), *Restoration costs* (maintenance mean 433,367.58€ yr^{-1}; investments 1,047,636€ over 8 years; 2024 total ~564,308€).
- **Risk management costs:** *Flood control/drainage* (average ~1 flood event yr^{-1}, with two events in 2024), *Coastal protection/marine submersion* (coastal barrier area, multi-temporal satellite analysis).
- **Environmental co-benefits linked to socio-economics:** *Global climate regulation* (site-type mean GWP from CO_2/CH_4 fluxes: −2.60 t CO_2eq ha^{-1} yr^{-1} across preserved/restored/altered sub-sites at time of study), *Water flow improvement* (WFI), *Groundwater recharge* (E/R qualitative status >1, i.e., extraction exceeds recharge), *Air quality* (ICQA average "Good–Fairly Good" → 5.5), *Fire prevention* (regional burned area). These were included because stakeholders consistently value environmental performance as a precondition for socio-economic acceptability.

A stakeholder workshop, held in Port de Sagunt, on 21st January 2025, gathered 16 participants (local/regional government, academia/projects, NGOs). Stakeholders rated themes (environmental, socio-economic, socio-cultural), categories, and criteria; weights were computed from these ratings. We document the imbalance (no industry present in the main workshop) as a limitation.

Three restoration scenarios were scored against all indicators:

1. Option 1 – Recovery of traditional irrigation network (Master Plan measures): reinstate/upgrade ditches and hydraulic connectivity; includes wastewater diversion and heritage irrigation structures.

2. Option 2 – Land-use changes and nature-based solutions (NbS): expand/reconfigure natural areas, dune/barrier reinforcement, extensive grazing/vegetation management to improve resilience and public access.
3. Option 3 – Vegetation/soil management for carbon markets: implement actions aligned with offset/compensation schemes to maximize GWP reduction and long-term financing.

For each indicator, expert elicitations specified expected trends per option (e.g., hydroperiod months, employment, costs, etc.).

Scenario scores were normalized using Min–Max, Max, and Vector methods to test sensitivity of rankings to scaling assumptions.

The Max method normalizes each indicator by dividing its value by the maximum observed value across scenarios:

$$v_{ij} = \frac{a_{ij}}{\max_i a_{ij}}$$

where $a_{ij}$is the raw value of indicator $i$for scenario j. This approach preserves proportionality among scenarios, meaning normalized values reflect relative differences (e.g., a value twice as large remains twice as significant after normalization). The highest value is scaled to 1, and others are expressed as fractions of this maximum.

The Min-Max method rescales indicator values between 0 and 1 based on the minimum and maximum observed values:

$$v_{ij} = \frac{a_{ij} - \min_i a_{ij}}{\max_i a_{ij} - \min_i a_{ij}}$$

Here, the minimum value is always normalized to 0 and the maximum to 1, regardless of their relative magnitude. This method facilitates comparison across indicators but does not capture the intensity of differences between scenarios.

The vector method normalizes each indicator by dividing its value by the square root of the sum of squared values across scenarios:

$$v_{ij} = \frac{a_{ij}}{\sqrt{\sum_i a_{ij}^2}}$$

This converts all attributes into dimensionless units, enabling inter-attribute comparison. However, the resulting scale length varies, which can complicate interpretation.

Weighted sums across indicators produced final MCA scores per scenario. We also ran a simple cost-sensitivity check (vector method) to explore when higher costs would erode Option 1's advantage.

3. Results

3.1. Environmental Characterization of water and sediment

To assess differences in environmental conditions among the studied subsites, Principal Coordinates Analyses (PCoA) based on physicochemical variables of water and sediment were performed for the spring samples. The PCoA analysis of water variables revealed a clear spatial ordination of the samples (**Fig. 2a**), where the first two axes jointly explained 66.8% of the total variation. The first axis (PCO1, 50.2%) defined the main environmental gradient, clearly separating sites according to their conservation status. Well-preserved sites (P1 and P2) clustered at the negative end of the axis, strongly associated with vectors for nutrients (TP, TN, PO4, NH4), dissolved organic carbon (DOC), conductivity (Cond), chlorophyll-a (Chl-a), and pH. In contrast, altered (A1, A2) and Restored (R1, R2) sites were mostly positioned towards the positive end of PCO1, correlating with greater water depth and nitrate/nitrite (NOx). The second axis (PCO2, 16.6%) reflected internal variability within each category, separating specific subsites. This axis notably distinguished R2 (positive values, associated with temperature and oxygen) from R1, as well as P1 from P2, and A1 from A2, highlighting environmental heterogeneity between replicates of the same management type.

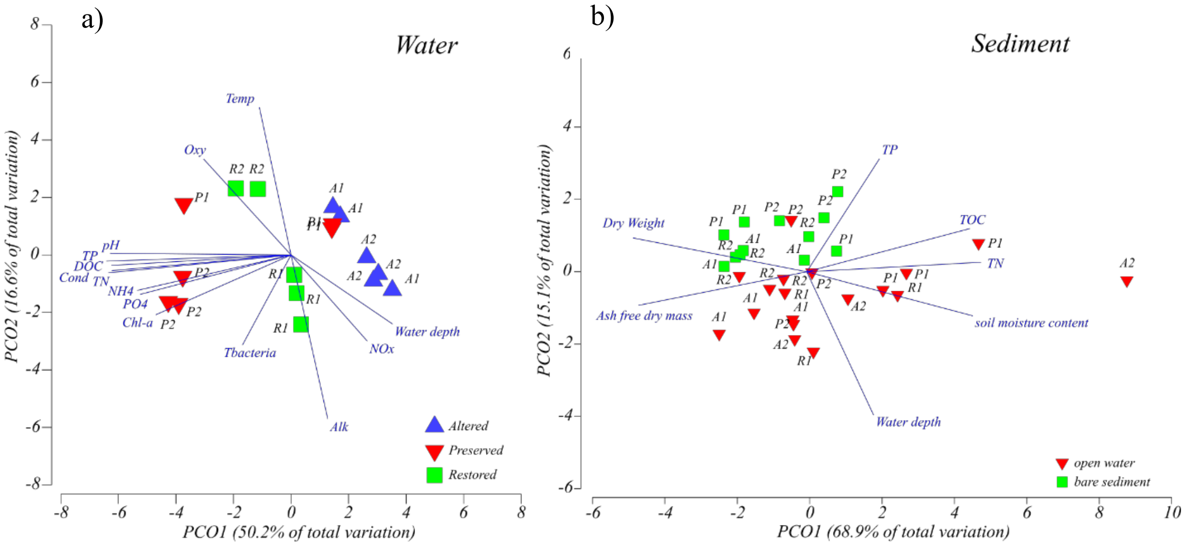

Figure 2. Principal Coordinates Analysis (PCoA) **a.** for water, **b.** for sediment illustrating the environmental variability across subsites in Marjal del Moros. The ordination is based on Euclidean distances calculated from normalized physicochemical variables measured in water

and sediment. Vectors (arrows) indicate the direction and magnitude of the environmental parameters driving the separation between sites along the first two axes. Environmental Variables abbreviations: Temp: Temperature; Cond: Conductivity; Oxy: Dissolved oxygen; Chl-*a*: Chlorophyll-*a*; Tbacteria: Total bacterial abundance, DOC: Dissolved organic carbon, NH4: Ammonium, NOx: nitrate + nitrite, PO4: Ortophosphate, TN: Total Nitrogen; TP: Total Phosphorus; TOC: Total organic carbon.

Principal Coordinates Analysis (PCoA) based on physico-chemical variables of sediment samples revealed a spatial ordination of the sites, in which the first axis (PCO1) alone explained most of the total variance (68.9%) (**Fig. 2b**). This axis defined a marked trophic and mineralization gradient: nutrient (TP, TN) and organic content (TOC, soil moisture content) vectors exhibited a strong positive correlation with PCO1, closely associated with subsites A2 and P1, which were positioned at the positive end of the axis. In contrast, sites A1, P1, and R2 (bare sediment samples) clustered on the opposite side (negative PCO1 values), correlated with higher dry weight and ash-free mass, indicative of more consolidated and less organic sediments. Notably, the Restored subsites (R1, R2) exhibited intermediate values distributed along the axis, indicating that these sediments are more heterogeneous. The second axis (PCO2, 15.1%) clearly separated sediments collected beneath the water column (open water samples) from bare sediment samples collected at points without standing water.

3.2. Microbial characterization of Sediment

Taking spring season as a model for the community composition in sediment, the Principal Coordinates Analysis of microbial community at level family reveals that methane-cycling functional guilds had a complex pattern driven by both management and hydrology (**Fig. 3**). The first axis (PCO1, 34%) clearly separated subsites P2 and R2—which were located at the negative end and associated with groups such as *Beijerinckiaceae*—from the rest of the samples. At the opposite end (positive PCO1 values), the vast majority of vectors for methanotrophic bacteria (e.g., *Methyloligellaceae*, *Methylomonadaceae*) and methanogenic archaea (e.g., *Methanosarcinaceae*) were projected, coinciding with a clear cluster of samples collected under the water column ("Open Water") from the Altered (A1, A2) and Restored (R1) sites. This arrangement suggests that permanent inundation in these sites, regardless of their restoration status, favors the development of more diverse and abundant microbial consortia linked to methane metabolism.

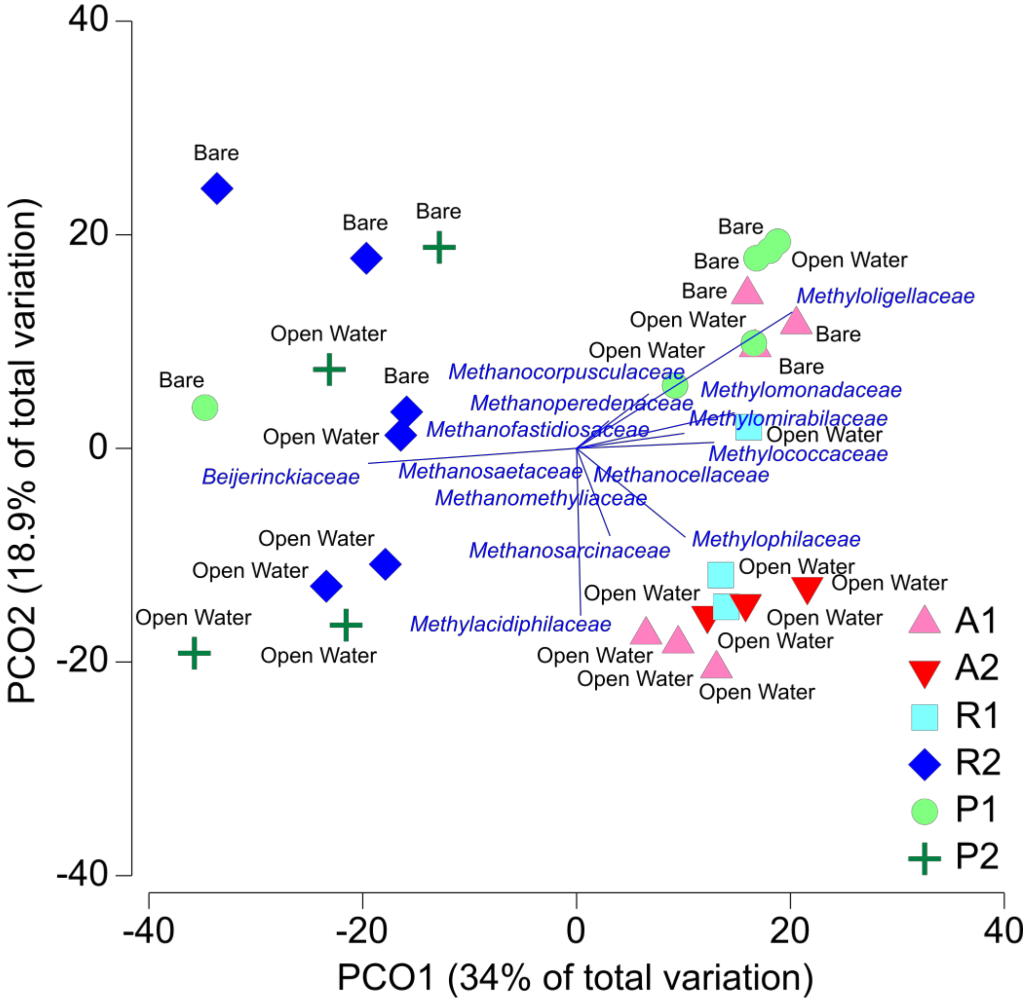

Figure 3. Principal Coordinates Analysis (PCoA) illustrating the microbial community variability (Family level) across subsites y Marjal del Moros. The ordination is based on Bray-Curtis distances calculated from standardized microbial composition (complete ZOTU table) measured in water and sediment. Subsites: A1/A2: Altered; P1/P2: Well-Preserved; R1/R2: Restored. Only taxa methane related are plotted.

The second axis (PCO2, 18.9%) reflected the determining effect of water cover at the time of sampling, separating submerged samples (negative values) from bare sediment samples ("Bare"). In this regard, samples from P1 and the emerged fraction of A1 clustered in the positive quadrant of PCO2, distant from the main vectors of methanotrophs typical of aquatic environments. This highlights that seasonal desiccation exerts a strong selective pressure on the functional community, differentiating it from permanently flooded sediments.

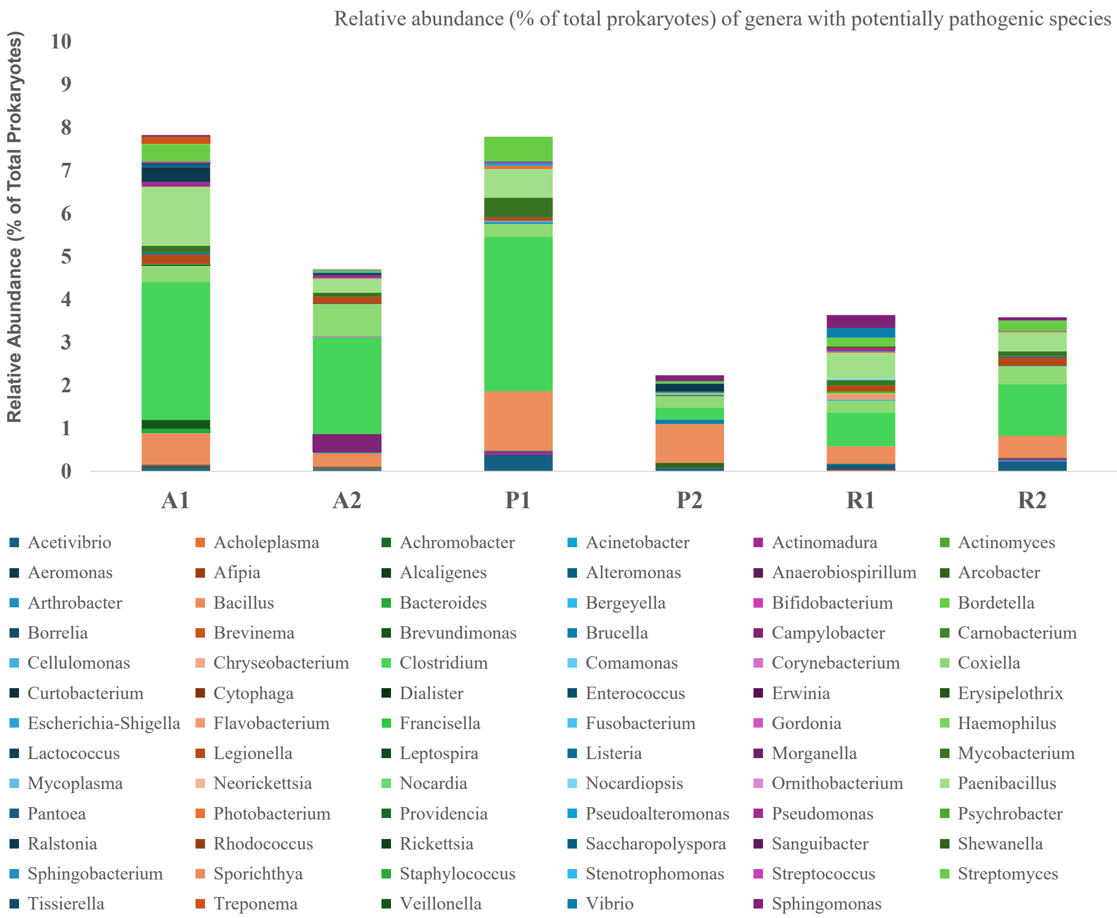

Figure 4. Relative abundance (%) of prokaryotic genera containing potentially pathogenic species in sediment samples.

The cumulative relative abundance of genera harboring potentially pathogenic species was moderate, ranging between 2% and 8% of the total prokaryotic community (**Fig. 4**). Most of this fraction was dominated by genera ubiquitous in soils and sediments, such as *Clostridium*, *Bacillus*, and *Paenibacillus*. These groups, although harboring pathogenic strains, comprise mostly free-living species typical of the natural dynamics of organic matter decomposition in wetlands, frequently acting only as opportunistic pathogens rather than as a direct sanitary threat.

Nevertheless, from the perspective of management and ecosystem services, the widespread detection of specific indicators of fecal contamination is relevant. Although their relative abundance was low, their ubiquitous presence in all samples—regardless of conservation status—signals a diffuse anthropogenic pressure throughout the marsh. Specifically, marker genera such as *Escherichia-Shigella* appeared in all subsites, albeit always maintaining marginal relative abundances below 0.05%. Similarly, *Arcobacter*, a genus frequently associated with wastewater, was detected across the entire wetland, yet with values consistently lower than 0.1%.

When examining differences between treatments, it was observed that the relative abundance of potentially pathogenic genera was not distributed uniformly but rather appeared linked to substrate characteristics. The highest percentages of these groups were consistently recorded in subsites A1, A2, and P1 (**Fig. 4**), coinciding with sediments presenting a higher organic and nutrient load. In contrast, the Restored subsites (R1 and R2) exhibited a notably different pattern: not only did they present the lowest abundance percentages in the study, but they also displayed high similarity to one another. This homogeneity in the restored sites indicates that management measures have succeeded in stabilizing sediment conditions, reducing intra-class variability and mitigating the presence of risk-associated communities linked to the organic degradation observed in altered zones and specific points of the preserved zones.

3.3. Functional Assessment

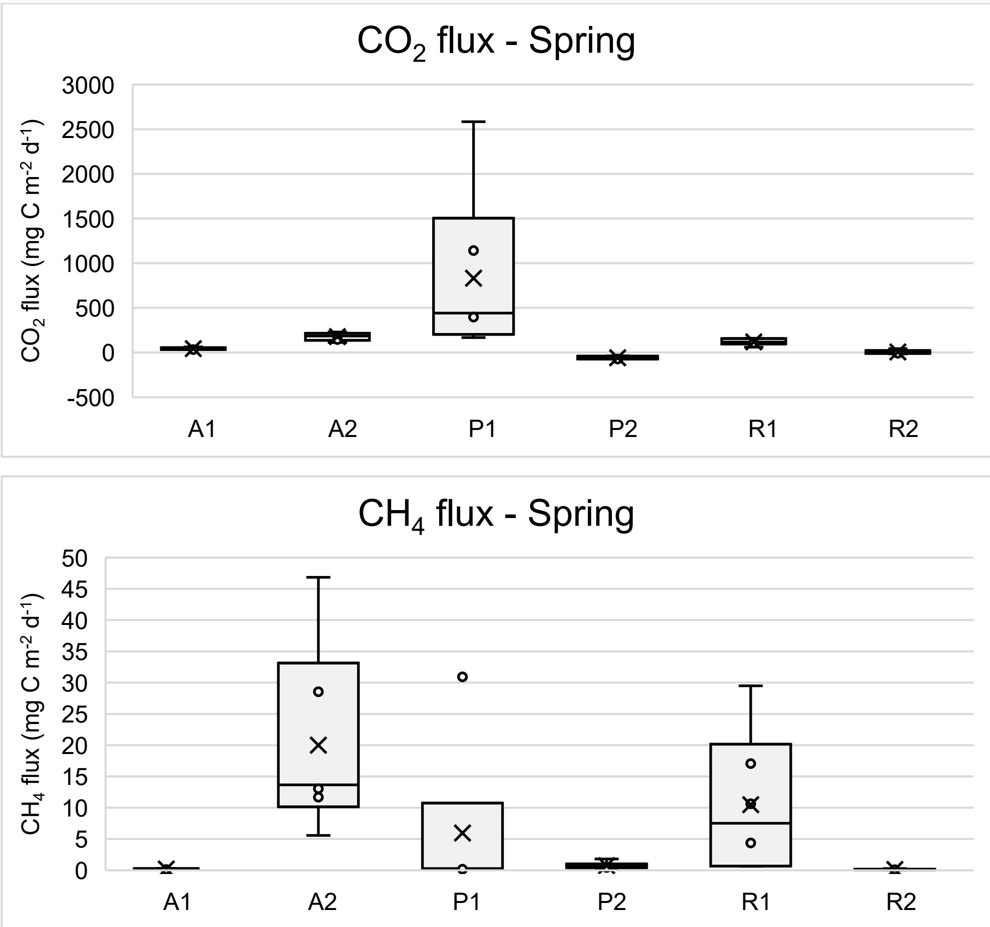

Figure 5. Boxplots showing seasonal variability and conservation-status differences in greenhouse gas fluxes (CO_2 and CH_4 in mg C m^{-2} d^{-1}) across subsites of Marjal dels Moros during the Spring campaign (Altered: A1, A2; Restored: R1, R2; Well-preserved: P1, P2).

Greenhouse gas fluxes measured in spring revealed strong spatial variability among subsites, reflecting the combined influence of hydroperiod, sediment properties, and microbial composition (**Fig. 5**). CO_2 dominated carbon efflux across all conditions, while CH_4 fluxes were comparatively lower but provided a sensitive indicator of reduced conditions and methanogenic activity.

Altered subsites exhibited contrasting behaviours. A2 showed elevated CO_2 emissions (178.14 ± 43.56 mg C m^{-2} d^{-1}) and a pronounced CH_4 hotspot (19.99 ± 15.18 mg C m^{-2} d^{-1}), consistent with its position in the environmental ordination (**Fig. 2**) as nutrient-rich and waterlogged, and its microbial profile (**Fig. 3**) dominated by methanogenic archaea (*Methanosarcinaceae*) and aquatic methanotrophs. In contrast, A1 displayed much lower CO_2 fluxes (43.01 ± 11.91 mg C m^{-2} d^{-1}) and negligible CH_4 release (0.19 ± 0.07 mg C m^{-2} d^{-1}), aligning with its drier sediment characteristics and reduced abundance of methane-cycling guilds.

Well-preserved sites showed the widest functional divergence. P1 recorded extremely high CO_2 fluxes (831.77 ± 927.27 mg C m^{-2} d^{-1}), likely driven by transient aerobic mineralization during exposure, whereas P2 acted as a net CO_2 sink (−58.82 ± 16.42 mg C m^{-2} d^{-1}) with minimal CH_4 emissions (0.73 ± 0.55 mg C m^{-2} d^{-1}). This contrast mirrors their structural differences: P1 sediments were organic-rich and moist, while P2 exhibited consolidated, mineral substrates. Microbial ordination confirms this pattern, with P2 clustering alongside R2 in the negative quadrant of PCO1 (**Fig. 3**), associated with *Beijerinckiaceae* and low methanogen abundance, explaining its negligible CH_4 flux.

Restored subsites displayed intermediate and more stable fluxes. R1 emitted moderate CO_2 (119.81 ± 36.72 mg C m^{-2} d^{-1}) and CH_4 (10.47 ± 11.27 mg C m^{-2} d^{-1}), reflecting partial recovery of hydroperiod and salinity but persistent organic enrichment. In contrast, R2 exhibited near-neutral CO_2 exchange (6.61 ± 21.57 mg C m^{-2} d^{-1}) and negligible CH_4 release (0.12 ± 0.08 mg C m^{-2} d^{-1}), paralleling its structural position as a drier site and its microbial similarity to P2, both characterized by reduced methanogenic guilds and dominance of aerobic taxa. This convergence between R2 and P2 underscores how hydroperiod and sediment consolidation jointly constrain methane cycling, reinforcing the role of structural recovery in shaping functional outcomes.

Overall, the integrated evidence indicates that hydrological state and substrate quality govern both microbial assemblages and GHG fluxes. Permanently inundated, nutrient-rich zones (e.g., A2) favour methanogenesis and elevated CO_2 emissions, while sites with seasonal exposure and higher salinity (e.g., P2, R2) tend toward lower or even negative CO_2 fluxes and minimal CH_4 production. These findings highlight hydroperiod management and salinity control as critical levers for climate-relevant functioning in Mediterranean coastal wetlands.

3.4. Socioeconomic Dimension

Stakeholder priorities and indicator performance

Fig. 6 compiles the results from the stakeholders' criteria for a restoration in Marjal dels Moros. Local stakeholders assigned the highest priority to the Habitats category, which received a weight of 10%. Within this category, emphasis was placed on the preservation of aquatic and terrestrial habitats that may be affected during or after restoration interventions.

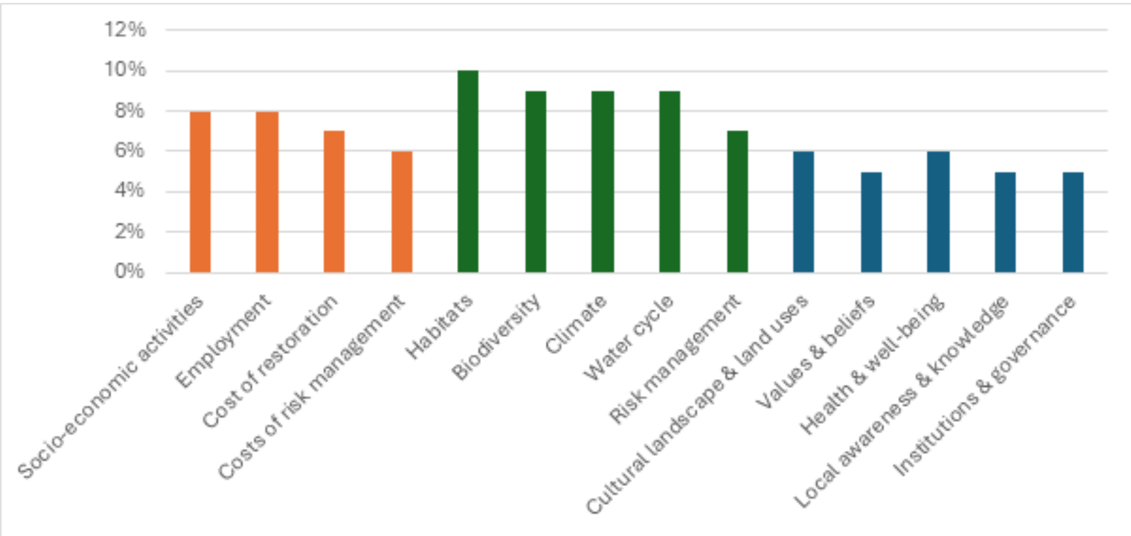

Figure 6. Comparison of the weight of criteria when considering a restoration project, according to Marjal dels Moros' stakeholders (16 respondents)

The categories Biodiversity (species richness), Climate (global climate regulation), and Water Cycle ranked closely behind, each with a weight of 9%. Although the remaining categories scored below 9%, they are not considered negligible; rather, they are perceived as less critical compared to environmental and socio-economic dimensions.

Notably, socio-cultural categories received lower weights relative to environmental and economic ones.

Within the Socio-economic category, criteria were distributed relatively evenly, indicating balanced consideration of activities. However, Water Provisioning emerged as slightly more important (30%) compared to Industrial Activities (20%).

For categories comprising two criteria—such as Costs of Risk Management (flood control and drainage; erosion and coastal protection), Water Cycle (water flow improvement; groundwater recharge), Risk Management (air quality improvement; fire prevention), Cultural Landscape and Land Uses (accessibility to public blue/green areas; cultural heritage), and Local Awareness and Knowledge (scientific research; educational and recreational interest)—weights were nearly equivalent between paired criteria. This suggests that both aspects within each category should be considered equally in restoration planning. Categories represented by a single criterion should be interpreted based on their individual weight.

Detailed weights for all criteria, as reported by 16 stakeholders from Marjal dels Moros, are provided in **Supplementary Table 1**.

Scenario comparison

- **Min–Max normalization:** Option 2 (Land-use changes & NbS) ranked highest (0.68), outperforming Option 1 (0.43) and Option 3 (0.40). This result indicates broader, positive contributions across many indicators—particularly those weighted by hydrology and accessibility/resilience.
- **Max normalization:** Option 1 (Master Plan irrigation recovery) ranked slightly higher (0.66) than Option 2 (0.63) and Option 3 (0.59), driven by strong benefits for Global climate regulation, Cultural heritage (restoration of historic ditches), and Employment (temporary jobs).
- **Vector normalization:** Option 1 again led (0.64) with Option 2 and Option 3 very close (0.62 each), confirming that practical hydraulic reconnection plus heritage works deliver a favourable mix of stakeholder-weighted benefits despite higher costs.

Table 1: Normalized scores per criterion and per option, and global MCA score Marjal dels Moros case pilot.

CRITERIA	Results Op1 Normalised value	Results Op2 Normalised value	Results Op3 Normalised value	Results Op1 Normalised value "Min Max"	Results Op2 Normalised value "Min	Results Op3 Normalised value "Min	Results Op1 Normalised value	Results Op2 Normalised value	Results Op3 Normalised value
Agriculture	1,00	0,62	0,73	1,00	0,00	0,30	0,72	0,44	0,53
Water provisioning (Water availability for nature conservation)	1,00	0,92	0,79	1,00	0,60	0,00	0,64	0,58	0,50
Interactions with industrial sector	0,00	0,00	1,00	0,00	0,00	1,00	0,00	0,00	1,00
Tourism / Recreational activities	0,92	1,00	0,88	0,33	1,00	0,00	0,57	0,62	0,54
Jobs created or lost during/following restoration	1,00	0,55	0,51	1,00	0,09	0,00	0,80	0,44	0,41
Restoration costs (investments, maintenance...)	0,00	0,14	0,14	0,00	1,00	1,00	0,36	0,45	0,45
Flood control/drainage	0,43	0,62	0,00	0,69	1,00	0,00	0,53	0,69	0,18
Erosion / runoff . Coastal protection / marine submersion regulation	1,00	1,00	0,95	1,00	1,00	0,00	0,59	0,59	0,56
Land and aquatic habitats created/preserved or lost	1,00	1,00	0,95	1,00	1,00	0,00	0,59	0,59	0,56
Species richness	0,85	1,00	0,85	0,00	1,00	0,00	0,54	0,64	0,54
Global climate regulation	0,00	-0,19	-0,39	0,00	0,49	1,00	1,48	1,57	1,67
Water flow improvement	1,00	0,92	0,83	1,00	0,50	0,00	0,63	0,58	0,52
Groundwater recharge	0,10	0,10	0,00	1,00	1,00	0,00	0,44	0,44	0,38
Air quality improvement	0,91	1,00	0,95	0,00	1,00	0,00	0,55	0,60	0,58
Fire prevention	0,00	0,05	0,24	0,00	0,22	1,00	0,36	0,40	0,52
Accessibility to public blue green areas	0,67	1,00	0,67	0,00	1,00	0,00	0,49	0,73	0,49
Cultural heritage	1,00	0,14	0,14	1,00	0,00	0,00	0,98	0,14	0,14
Place attachment for spiritual, aesthetic, cultural reasons...	0,77	0,91	1,00	0,00	0,61	1,00	0,49	0,58	0,64
Mental health influence	0,92	1,00	1,00	0,00	1,00	1,00	0,54	0,59	0,59
Scientific research	0,75	0,86	1,00	0,00	0,43	1,00	0,49	0,57	0,66
Education & recreative interest	1,00	1,00	0,79	1,00	1,00	0,00	0,62	0,62	0,49
Participation in decision making and trust in institutions	0,67	0,67	1,00	0,00	0,00	1,00	0,49	0,49	0,73
MCA VALUE	0,66	0,63	0,59	0,43	0,68	0,40	0,64	0,62	0,62

4. Discussion

Integrating environmental structure, ecosystem function, and socio-economic outcomes

This study provides an integrated appraisal of a managed Mediterranean brackish marsh, showing how restoration modifies environmental structure (water and sediment properties; **Fig. 2**), reshapes benthic microbial assemblages (**Fig. 3**, **Fig. 4**), and alters greenhouse gas (GHG) emissions ((**Fig. 5**), with measurable implications for socio-economic priorities and decision-making (**Table 1**). Across the gradient of well-preserved, altered, and restored subsites, hydrology and salinity emerged as the principal organizers of both biogeochemical dynamics and stakeholder-valued services. This finding supports restoration strategies in coastal wetlands that elevate hydroperiod design, water-quality controls, and habitat heterogeneity as foundational levers for resilience and multifunctionality (Yang et al., 2017; Vélez-Martín et al., 2018). In the Marjal dels Moros, where historical engineering, water scarcity, and surrounding urban/industrial land uses complicate governance, the integrated assessment clarifies how targeted actions can move the system toward ecological integrity, climate benefits, and socially acceptable uses, consistent with EU policy frameworks, WFD and HD, (Latron et al., 2022) and the nature-based solutions agenda (Thorslund et al., 2017).

From a management perspective, the results support the view that restoring and maintaining environmental heterogeneity is central to enhancing wetland resilience and multifunctionality. Differences among sites in water characteristics, sediment properties, and biological communities appear to structure key functional processes, including GHG dynamics, and influence the capacity of the marsh to support ecosystem services prioritized in the Management Plan.

Environmental heterogeneity as a resilience asset

The ordination of physicochemical variables (**Fig. 2**) revealed a strong trophic/mineralization axis (PCO1; 68.9% variance) along which altered (A2) and one preserved subsite (P1) clustered with high TOC, TN, TP, and moisture, while other preserved and restored subsites aligned with drier, more mineral substrates. The second axis (PCO2; 15.1%) separated submerged open water, from bare sediments, highlighting water cover at sampling as a proximate driver of variability. Restored subsites (R1, R2) occupied intermediate, more dispersed positions, consistent with re-established heterogeneity under recovery. Ecologically, this mosaic limits single-state dominance (e.g., permanently inundated, eutrophic patches) and supports multiple functions and services (Vélez-Martín et al., 2018). In managed Mediterranean marshes, such heterogeneity buffers interannual climate variability (e.g., drought) and aligns with adaptive management prescriptions that favour diverse hydroperiods and salinity regimes (Rochera et al., 2025).

Microbial community structure: hydrological control of methane-cycling guilds

The microbial PCoA (**Fig. 3**) showed methane-cycling guilds tracking hydrological state rather than restoration label alone. Methanotrophic (*Methyloligellaceae*, *Methylomonadaceae*) and methanogenic (*Methanosarcinaceae*) families co-occurred predominantly in “open water” samples from altered sites (A1, A2) and one restored site (R1), while P2 and R2 grouped with taxa such as *Beijerinckiaceae* on the opposite side of the gradient. The second axis separated submerged from bare sediments, emphasizing seasonal desiccation as a selective filter that diminishes typical aquatic methanotroph signatures. These patterns indicate that water level and residence time modulate redox conditions and substrate supply, thereby governing methane-related metabolism, mechanistically consistent with the functional flux differences observed across conservation classes (Morant et al., 2020; Rochera et al., 2025).

From an ecosystem-services standpoint, **Fig. 4** shows low but ubiquitous detection of fecal-associated genera (e.g., *Escherichia-Shigella* <0.05%; *Arcobacter* <0.1%), implying diffuse anthropogenic (or waterfowl) inputs across all subsites. The cumulative relative abundance of potentially pathogenic genera was consistently higher in altered (A1, A2) and one preserved subsite (P1), while restored sites (R1, R2) had the lowest values and highest mutual similarity, evidence that restoration is stabilizing sediment conditions and limiting risk-associated microbiota tied to organic enrichment. These results argue for sustained management to curb nutrient-rich return flows and for hydroperiod designs that avoid prolonged, stagnant inundation in organic-rich sectors, thus supporting both ecological function and socially valued uses (Barbier, 2013).

Functional processes: sediment GHG fluxes and hydrology-first control

Our spring analysis demonstrates that GHG fluxes in Marjal dels Moros are tightly coupled to hydrological state, salinity gradients, and sediment structure, which in turn shape microbial community composition. This mechanistic linkage (hydrology-salinity-microbial guilds-GHG emissions) emerges as a central axis of ecosystem functioning and management relevance. Therefore, two complementary levers emerge for climate restoration: (i) preserve or recover salinity gradients that constrain methanogenesis by microbial guilds (Hartman-Wyatt et al., 2024); and (ii) manage hydroperiod and vegetation structure to enhance autotrophic uptake while avoiding persistent waterlogging in nutrient-rich zones that foster CH_4 hotspots (Beaulieu et al., 2019). Evidence from the Marjal dels Moros and related work suggests that saline conditions, intermittent exposure, and vigorous helophyte stands can yield lower net emissions or even net ecosystem carbon uptake, depending on nutrient status and vegetation productivity (Morris et al., 2012; Hagger et al., 2022).

Sites with permanent inundation and nutrient enrichment (e.g., A2) exhibited elevated CO_2 emissions and pronounced CH_4 hotspots, consistent with microbial profiles dominated by methanogenic archaea and aquatic methanotrophs. Conversely, subsites with seasonal exposure and higher salinity (e.g., P2 and R2) showed near-neutral or negative CO_2 fluxes and negligible CH_4 release, paralleling their consolidated sediments and microbial assemblages dominated by aerobic taxa and low methanogen abundance. These patterns confirm that restoration measures that re-establish hydroperiod variability and salinity gradients can suppress methanogenesis, stabilize carbon dynamics, and reduce climate-relevant emissions (Morris et al., 2012; Hagger et al., 2022).

Methodologically, the sediment-focused analyses are complemented by the study of Cabrera-Brufau et al. (under review), which was conducted concurrently with the present work within the same RESTORE4Cs project framework. While our study utilizes sediment core incubations to isolate the benthic biogeochemical drivers, Cabrera-Brufau et al. employed an ecosystem-scale approach using static chambers to measure net fluxes. This methodological duality offers a robust validation of carbon dynamics in Marjal dels Moros: the core assays elucidate the potential production capacity of the microbial community, whereas the chamber measurements integrate the modulating effects of the water column and vegetation structure. Consequently, the combination of both datasets bridges the gap between benthic metabolic potential and the realized atmospheric exchange.

This recognition of carbon cycle processes, spanning sediment fluxes, water column dynamics, and vegetative capture as illustrated by the combined findings of this study, (Morant et al., 2020), and Cabrera-Brufau et al. (under review), provides the essential baseline for Nature-based management for climate neutrality. Thus, restored subsites may mitigate climate change under Global Warming Potential (GWP units), whereas altered subsites have a warming effect. Within this framework, the microbiological characterization presented here serves as a crucial mechanistic addition, offering the process-level understanding to support interventions. This integration of functional ecology and microbial drivers may facilitate the shift from passive conservation to active mitigation, a strategy exemplified by the LIFE Wetlands4Climate project (LIFE Wetlands4Climate, 2024), which established Marjal dels Moros as a key pilot site. This project demonstrated that targeted adjustments in hydroperiod, vegetation, and soil management can effectively optimize the carbon balance and reduce the warming capacity, thereby translating scientific evidence into concrete emission abatement capacity.

The integration of structural and functional evidence underscores that hydrology-first management is not only a biophysical imperative but also a socio-economic lever. By controlling water regimes and salinity, managers influence microbial guild composition and GHG fluxes, which directly affect ecosystem services prioritized in policy frameworks, such as climate regulation, water quality, and biodiversity support. For example, reducing CH_4 emissions through salinity maintenance and intermittent drawdown enhances the wetland's contribution to global climate mitigation targets, while stabilizing sediment conditions improves habitat quality and reduces sanitary risks linked to pathogenic proxies.

These findings position hydroperiod and salinity management as foundational strategies for climate-based restoration. Measures such as diversifying water sources, curbing nutrient-rich inflows, reinstating seasonal drawdown, and maintaining saline gradients will optimize microbial processes toward aerobic pathways, minimizing methane production and promoting carbon sequestration. In turn, these functional improvements strengthen the delivery of ecosystem services valued by stakeholders, risk reduction, recreational opportunities, and cultural heritage, creating a direct bridge to socio-economic performance and governance considerations addressed in the next section.

Socio-economics and governance: stakeholder preferences and scenario trade-offs

Stakeholders prioritized environmental outcomes (44% aggregate weight), with habitats (10%), biodiversity (9%), climate regulation (9%), and water cycle (9%) leading. Socio-economic (29%) and socio-cultural (27%) themes were valued but ranked second, reflecting local expectations that ecological integrity is a precondition for acceptable public use and long term social license. Within socio-economics, water provisioning outranked industrial activity, and risk-management criteria (flood control/coastal protection) carried meaningful weights, consistent with coastal hazard exposure and regional water scarcity (Geijzendorffer et al., 2019). Multi-criteria analysis (**Table 1**) revealed near-parity among restoration scenarios, with the top option depending on the normalization method: Option 2 (land-use changes & NbS) ranked first under Min–Max scaling (0.68), whereas Option 1 (recovery of traditional irrigation network) led under Max (0.66) and Vector (0.64); Option 3 (vegetation/soil management for carbon markets) was consistently close behind (0.59–0.62).

Workshop representation skewed toward government, academia, and NGOs, with no direct industry participation, an imbalance that may have amplified biocentric preferences and elevated environmental weights. Subsequent co-design should correct this governance gap to ensure durable social license in an industrial hinterland, pairing ecological evidence with risk reduction (floods, coastal erosion) and transparent cost-sharing. Aligning local actions with basin-scale water governance (e.g., wastewater and agricultural return-flow management) is essential to sustain function and public acceptance (Turner et al., 2000).

Management and policy implications

The convergence of structural, microbial, and flux evidence argues for hydroperiod management and restoration as the foundation of adaptive plans. Priority actions include: (a) diversifying water sources while curbing nutrient-rich inputs; (b) reinstating seasonal drawdown in selected cells to disrupt methanogenesis; (c) maintaining salinity gradients that suppress CH_4; and (d) optimizing hydraulic connectivity to balance residence time and oxygenation. These interventions reduce CO_2/CH_4 emissions, mitigate microbial contamination proxies, and enhance habitat heterogeneity, arose explicitly valued in the management plan and supportive of WFD/HD objectives.

Restored subsites' lower emissions and reduced risk-associated microbiota suggest that vegetation management (helophyte establishment, rotational mowing) coupled with sediment stabilization can consolidate functional gains. Managers should target mosaics that couple high autotrophic production with intermittent sediment air-exposure, avoiding extensive, nutrient-rich permanent waters that harbor methanogenic guilds (Morant et al., 2020; Hartman-Wyatt H. et al., 2024).

Routine programs should complement traditional structural/biological metrics with functional ones, such as seasonal CO_2 and CH_4 fluxes determinations, sediment TOC, and microbial guild markers, to quantify restoration success beyond habitat structure. Embedding such indicators into policy reporting (e.g., site-level climate regulation metrics used in the MCA) strengthens funding cases and aligns with climate-resilience objectives (Thorslund et al., 2017; Seddon et al., 2020).

MCA results justify combining hydraulic heritage recovery (Option 1) with NbS land-use reconfiguration (Option 2), while selectively piloting carbon-market actions (Option 3) wherever monitoring capacity and verification are robust. Managers should treat the cost sensitivity as a planning signal and pair it with stakeholder willingness-to-pay an acceptable cost sharing instruments to avoid under-resourced maintenance (Anglada et al., 2025).

Limitations of the biophysical approach and future directions

Our sediment-focused flux approach isolates benthic drivers but does not close the ecosystem carbon budget; thus combining core incubations with parallel chamber measurements over vegetation/water columns would refine source/sink attribution and better represent the wetland/atmospheric exchange. Temporal coverage underscores strong seasonality; multi-year monitoring is needed to detect interannual trends and management effects. Microbial guild inference from 16SRNA gene taxonomic patterns should be complemented with functional gene assays (e.g., *mcrA* for methanogenesis, *pmoA* for methanotrophy) to track process-level responses to specific restoration actions. Finally, diffuse anthropogenic inputs detected via microbial proxies appeal to basin-scale interventions (wastewater diversion, agricultural return-flow reductions) beyond site boundaries to secure long-term gains in ecological integrity and social acceptance (Turner et al., 2000).

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CONFLICTS OF INTEREST

None

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this work the authors used AI (COPILOT) in order to identify potential improvements in text readability and for coding syntax support during data processing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

AUTHOR CONTRIBUTION STATEMENT

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Writing – original draft: AC, DM, AP, CR, MJP
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Supplementary material

Supplementary Material 1: Workshop methodology (Source: Anglada et al. 2025)

The selection of criteria and indicators resulted from a collaborative work between Vertigo Lab, MedWet and the case pilot leader at University of Valencia. Representatives of the managing authority were particularly involved in this case pilot given their interest in updating the draft Master Plan with inputs from stakeholders. Moreover, other local stakeholders were involved, as 14 interviews were led to find out more about the context and issues of the site, and to collect data that would be useful for the MCA.

Definition of indicators

Agriculture: agricultural surface was selected as an indicator, based on Corine Land-Cover 2018 data Class 2 “Agricultural Areas”, since the data was easily available. Thanks to WP6 work, it was possible to tailor it to the exact perimeter of the study. According to CLC 2018 data, **2,700 hectares** of land are classified as “Agricultural Areas”. According to expert knowledge, this indicator is expected to moderately increase in case of option 1, slightly decrease in case of option 2 and very slightly decrease in case of option 3.

Water provisioning and availability for nature conservation: the number of months per year when the wetland remains inundated (hydroperiod) was selected as an indicator for this criterion and attained **9** in 2024. This is determined using the inundation level in the wetland, measured at strategic points using limnimeters (water-level gauges) to obtain a continuous record of water-level variations (e.g., meters above a reference point) over time. This information was found using IZONASH, a Wetland Monitoring Program. According to expert knowledge, this indicator is expected to slightly increase in case of option 1, very slightly increase in case of option 2 and very slightly decrease in case of option 3.

Interactions with the industrial sector: next to the wetland – just outside the limits of the protected areas – works are underway to build Europe’s biggest gigafactory while extending the size of an existing industrial park. The construction of these facilities has a severe impact on the catchments’ hydrological and ecological connectivity and is expected to reduce water availability for the wetland. The lack of involvement of the private sector – particularly the industrial sector – is therefore considered one of the main barriers to preserve and restore the wetlands. With the goal of involving the private sector in restoration, the University of Valencia, through the LIFE Wetlands4Climate project has been working to create a carbon offset or carbon compensation scheme. This option is captured by the scenario of option 3, as opposed to option 1 and 2, which reflect on the current scenario where **no scheme** is set up.

Tourism / Recreational activities: the number of users of the protected area per year was selected as an indicator to represent this criterion, based on data published in the annual report of the Centre of Environmental Education of the Valencia Region (CEACV). On their website, it is estimated that approximately **10,000 people** visited the centre in 2024. According to expert knowledge, this indicator could experience a moderate increase in the case of option 2 (linked to the development of wilder natural areas),a rather slight increase with option 1, because of the recovery of traditional irrigation ditches, while barely increasing in the case of option 3.

Jobs created or lost during/following restoration: At Marjal dels Moros, there are 6 permanent staff members involved in the restoration of the site, as well as 7 temporary workers, making up to a total of **13 persons.** According to the data shared by the managing authority, the plan is to create additional 15 to 20 temporary jobs in case of option 1, a little less in case of option 2 and even less in case of option 3, although the indicator is still increasing in all options.

Restoration costs (investments, maintenance…): According to the draft Master Plan of Marjal dels Moros, €433,367.58 per year are needed on average for the maintenance of the area, whereas investments over the last eight years accounted for €1,047,636 in total, so €130,940.50 per year on average. Thus, for 2024, the overall costs for Marjal dels Moros have been estimated at **€564,308.08**. Currently, the investments planned for 2025-2026 are estimated at €978,125.76 meaning that the average per year of the overall costs in case of option 1, which follows the Master plan, are expected to reach €922,430.46. High maintenance and investment costs may be perceived as an obstacle to some SH when implementing a restoration project. This may depend on the site capacity to finance or on the source of financing. Even if costs can be seen as a positive contribution, enabling projects with benefits for SH and the ecosystems, financing capacities may be limited. High costs might thus be perceived as too important in comparison to what could be socially accepted. This indicator's value is then considered as negative for the purpose of this MCA. According to the local team, these costs are expected to still fairly increase in case of option 2 and option 3, but less than for option 1.

Flood control / drainage: Since 2021, one flood event has happened per year between Sagunto and Puçol, according to the local news. Two happened in 2024, one in July and one in October. The estimated average for the last years is **one flood event** per year.

Floods evidently cause harm to populations; therefore, an increase of this indicator's value is considered as negative for this case pilot. According to expert knowledge, option 1 and 2 will play a moderate role in reducing flood occurrence; although more important in the case of option 2, while barely increasing in the case of option 3.

Erosion / runoff and Coastal protection / marine submersion regulation: Changes in the shoreline considering the surface area of the coastal barrier is the indicator selected to represent this criterion. According to Multitemporal satellite imagery analysis (e.g., Sentinel-2, Landsat), they represent **28 hectares** in 2024. According to expert knowledge, this indicator is expected to very slightly increase in case of option 1 and option 2 and to remain stable in case of option 3. This is because only options 1 and 2 are expected to have a direct effect on the wetland's hydrological functioning, which can promote increase and/or stabilization of the coastal barrier. As pointed out by stakeholders throughout the different participatory moments (workshops, interviews), effective measures to reduce this risk require stronger investments by the coastal management authority.

Land and aquatic habitats created/preserved or lost: the surface of natural habitats was chosen as an indicator to represent this criterion and is estimated to cover **600 hectares** of the area. The data was collected thanks to WP6 work, based on the CLC 2018 classification "Natural drylands" and "Natural wetlands". According to expert knowledge, this indicator is expected to very slightly increase in case of option 1 and option 2 and to increase a little less in case of option 3. In addition, option 1 – in particular the diversion of wastewater – is expected to improve the status of brackish habitats, potentially helping abate carbon and GHG emissions.

Species richness: the number of species of communal interest under annex II of Habitat and Bird Directive was chosen as an indicator as these species are the most important ones and their diversity is a good indicator of a healthy ecosystem. As shown by the Natura 2000 viewer, **9** of these species are identified in Marjal dels Moros. According to expert knowledge, this indicator is expected to very slightly increase in case of option 1 and option 3 and to moderately increase in case of option 2.

Global climate regulation: to represent this criterion, GWP derived from CO_2 and CH_4 fluxes was chosen as an indicator since it was measured by WP4 and is very specific to the case pilot. As GWP values were recorded only for the subsites – and not for the whole Marjal dels Moros - the value taken as a reference for this analysis is the mean GWP of two well-preserved sub-sites, two restored sub-sites and two altered sub-sites. The value may differ slightly to significantly depending on the case pilot, and whether the sub-site was altered, restored, or well-preserved. For the selected sites, it is currently estimated at **-2,60 tons of CO_2eq/yr/ha** from WP4 data available at the time of the study. The goal of this project being to help climate mitigation by restoring wetlands, the release of GHG and therefore the increase of this indicator's value, is considered as negative for this case pilot. According to expert knowledge, this indicator is expected to very slightly decrease in case of option 1, slightly decrease in case of option 2 and fairly decrease in case of option 3.

Water flow improvement: to represent this criterion, the local team has developed a custom indicator: the Water Flow Index (WFI). It reflects the number and equilibrium of active inflows and outflows. It prioritizes quantity but is adjusted for balance between the components. The formulation penalizes scenarios in which inflows and outflows are highly unbalanced, even if the total number is high. Accordingly, calculation is described as follow: **WFI = (nb Inflows + nb Outflows) × [1 − |nb Inflows − nb Outflows | / (nb Inflows + nb Outflows)]** and is currently evaluated at **6**. To interpret this index value, it should be considered that it is not based on a predefined scale (like 0 to 10), so it can take any positive value depending on the characteristics of each site. Therefore, it is feasible to assess trends over time or to compare similar systems, rather than for absolute benchmarking. An increase in WFI is positive, as it indicates either an increase in total water connections, which generally improves hydrological function and ecological resilience, or a more balanced flow configuration, which is desirable for the site's stability. In Marjal dels Moros, a WFI of 6 already reflects a relatively good configuration, but further increases would improve hydrological setup on the site. Again, we do not expect that option 3 has a direct effect in this hydrological setup. According to the local team, this indicator is expected to slightly increase in case of option 1, very slightly increase in case of option 2 and remain stable in case of option 3.

Groundwater recharge: the aquifer overexploitation has been selected as an indicator to represent this criterion, as a qualitative assessment based on a quotient between extraction (E) and recharge (R), defined as: $E/R < 1$ (i.e., $E < R$); $E/R = 1$ (i.e., $E = R$); $E/R > 1$ (i.e., $E > R$). Currently, and according to the data available from the Cartographic Institute of Valencia, this value stands at $E/R > 1$, since extraction exceeds recharge. In the context of recurrent extreme weather events, including droughts, it is seen as sensible to not overexploit aquifers; therefore, an increase of this indicator's value is considered as negative for this case pilot. According to expert knowledge, this indicator is expected to very slightly decrease in case of option 1 and option 2 and remain stable in case of option 3.

Air quality improvement: the ICQA (Spanish Air Quality Index) is based on a maximal subindex of PM10, PM2.5, NO_2, O_3, SO_2 and CO – scaled by health thresholds. Spain uses its own national Air Quality Index (ICQA), which is based on EU legislation and differs from the US AQI in scale and classification**.** The average value for 2024 was estimates to be **Good-Fairly Good** which translates into a **5.5** for the purposes of the MCA[29]. According to expert knowledge, this indicator is expected to remain stable in case of option 1, very slightly increase in case of option 2 and increase a little less in case of option 3.

Fire prevention: the historical fire occurrence measured as burned area was selected as an indicator for this criterion. According to the Cartographic Institute of Valencia, **21.89km²** were burned on average per year from 2013 to 2022. Fire incidents evidently cause harm to populations and nature; therefore, an increase of this indicator's value is considered as negative for this case pilot. According to expert knowledge, this indicator is expected to very slightly decrease in case of option 1, decrease a little more in case of option 2 and slightly decrease in case of option 3. Moreover, data collected on fire events suggests a concentration of provoked fires in former agricultural land, and from which land farmers were expropriated.

Accessibility to public blue green areas: there are three access points to Marjal dels Moros, only **two** being currently in good condition and allowing accessibility. According to the draft Master plan, only in the case of option 2 would the third access point be renovated. In the case of the other two options, they would remain as they are.

Cultural heritage: So far, only **one historical construction** has been restored in the last decades, i.e. the building hosting the Centre for Environmental Education. As per the plans shared by the management authority, option 1 would enable restoration of 7 traditional irrigation ditches along 7,800 meters, leading to a significant increase in the number of heritage-related facilities that are restored. Options 2 and 3 aren't expected to have any influence on this criterion.

Place attachment for spiritual, aesthetic, cultural reasons: The indicator chosen to measure this criterion was the number of civil society organisations that deploy their activities in the area of the wetland – currently only **two**. The number of associations would be expected to increase very slightly in case of option 1 (potentially linked to an increase in agricultural activity) and moderately for option 2 – as a result of increased wilderness - and option 3 (related to restoration activities).

Mental health influence: to assess this criterion, a custom survey was developed by the University of Valencia, to find out about the perceived impact of the Marjal dels

Moros, considering its broad environmental context and nearby industrial areas, on the mental well-being of the local population. This survey was done face to face over a day, asking the questions to randomly selected visitors of Marjal dels Moros. According to this survey of 10 respondents, **60% of the people** who were interrogated value the role of the wetland for mental health. According to University of Valencia, this indicator is expected to very slightly increase in case of option 1 and slightly increase in case of option 2 and option 3.

Scientific research: Currently, there are **four ongoing research projects** linked with Marjal dels Moros. These include the LIFE project Wetlands4Climate, and three Horizon projects - BlueGreenGovernance, Soteria, and RESTORE4Cs. According to the local team, this indicator is expected to very slightly increase in case of option 1, slightly increase in case of option 2 and fairly increase in case of option 3.

Education & recreative interest: Currently, there are **two ongoing educational projects** linked with Marjal dels Moros: one focused on birds study led by the CEACV and another one for school-age children at Camp de Morvedre. According to the local team, this indicator is expected to fairly increase in case of option 1 and option 2 and very slightly increase in case of option 3.

Participation in decision making and trust in institutions: Before the launch of RESTORE4Cs, the wetland did not count on any participatory committee. Thanks to the stakeholder engagement activities organised by the project, **a first** Living Lab is being developed with the support of other research projects and local actors. A significant increase in the number of participatory units is only expected in the case of option 3 (as a result of the activities to develop offset or compensation schemes), whereas option 1 and 2 would have a minor impact.

Supplementary Table 1:

The weight that criteria should have when considering a restoration project, according to Marjal dels Moros' stakeholders (16 respondents)

Level 1 (Themes)	**Weight**	**Level 2 (Categories)**	**Weight**	**Level 3 (Criteria)**	**Weight**
Socio-economics	**29%**	Socio-economic activities	**8%**	Agriculture	27%
				Industrial activities	20%
				Tourism/recreational activities	23%
				Water provisioning	30%

		Employment	**8%**	Jobs created or lost during/following restoration	
		Cost of restoration	**7%**	Investment, maintenance costs...	
		Costs of risk management	**6%**	Flood control / drainage	51%
				Erosion/Runoff / Coastal protection / marine submersion regulation	49%
Environment	**44%**	Habitats	**10%**	Aquatic and terrestrial habitats created/preserved or lost	
		Biodiversity	**9%**	Species richness	
		Climate	**9%**	Global climate regulation	
		Water cycle	**9%**	Water flow improvement	47%
				Groundwater recharge	53%
		Risk management	**7%**	Air quality improvement	52%
				Fire prevention	48%
Socio-cultural	**27%**	Cultural landscape and land uses	**6%**	Accessibility to public blue green areas	49%
				Cultural heritage	51%
		Values and beliefs	**5%**	Place attachment for spiritual, aesthetic, cultural reasons...	
		Health and well-being	**6%**	Mental health influence	
		Local awareness and knowledge	**5%**	Scientific research	53%
				Education & recreative interest	47%
		Institutions and governance	**5%**	Participation in decision making and trust in institutions	