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Co-produced ecological monitoring of kelp ecosystems for adaptive management in a multiple-use marine protected area

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Abstract

Kelp-dominated coastal ecosystems support high biodiversity and artisanal fisheries but are increasingly exposed to interacting environmental and harvesting pressures, highlighting the need for ecological monitoring frameworks that can inform adaptive management. We developed a participatory monitoring framework for brown-algae meadows in the Lafken Mapu Lahual Multiple-Use Marine and Coastal Protected Area, southern Chile, integrating ecological field surveys (2014–2015), landing records (2000–2024), and a DPSIR-based co-design process involving 35 stakeholders, including artisanal fishers, Mapuche-Huilliche representatives, and government agencies. Spatial surveys revealed marked differences in population structure and associated biodiversity among sampling units. More than 95% of *Durvillaea incurvata* and 90% of *Lessonia spicata* individuals had holdfast diameters below 21 cm, whereas the southern sampling unit showed broader population size structures and greater associated faunal richness. Ecological evidence and local knowledge were integrated to identify five operational indicators and provisional quantitative management thresholds. Fishers contributed indicator species absent from the initial expert-derived list, illustrating how knowledge co-production can expand the ecological information available for monitoring. Estimated annual implementation costs ranged from USD 70,000 to 100,000, depending on the monitoring model. By linking spatial ecological patterns, extraction history, and participatory indicator development, the framework provides an integrated approach for monitoring kelp-dominated coastal ecosystems and supporting adaptive management in multiple-use marine protected areas.

Keywords: knowledge co-production; participatory monitoring; adaptive management; kelp ecosystems; multiple-use marine protected areas.

49 **Introduction**

50 Kelp forests and brown-algae meadows are among the most structurally important habitats
51 of temperate rocky coasts, supporting complex ecological networks, facilitating nutrient
52 cycling, and sustaining diverse benthic and fish assemblages. Along the Chilean coastline,
53 these habitat-forming species also underpin artisanal fisheries and coastal livelihoods,
54 creating strong ecological and socioeconomic linkages between kelp ecosystems and
55 human communities (Vásquez 2016; Vega et al. 2021; Malla et al. 2024; Mangan et al.
56 2025). Their ecological condition is shaped by interacting natural and anthropogenic
57 pressures, including hydrodynamic exposure, harvesting, storm events, and environmental
58 variability associated with ENSO, oxygen minimum zones, and shifts in coastal upwelling
59 (Pérez-Matus et al. 2017; Oyarzo-Miranda et al. 2023; Avilés and Parker 2024). These
60 pressures can alter kelp population structure, canopy development, associated biodiversity,
61 and recovery potential, highlighting the need for monitoring approaches capable of
62 detecting ecologically meaningful changes and translating them into management
63 responses.

64 Multiple-use marine protected areas provide an important setting for addressing this
65 challenge because biodiversity conservation must coexist with the sustainable use of marine
66 resources. Their effectiveness therefore depends not only on legal protection but also on
67 monitoring systems capable of detecting ecological change and supporting adaptive
68 management (Halpern et al. 2010; Ratner and Allison 2012). This challenge is particularly
69 relevant in coastal social-ecological systems, where biological diversity, artisanal
70 livelihoods, cultural identities, and multiple institutional actors interact within relatively
71 small geographic areas (Berkes 2004; Gelcich et al. 2010). In Chile, where MUMPAs cover

more than 1.3 million hectares and support thousands of artisanal fishers, limited ecological baselines, monitoring capacity, and stakeholder coordination continue to constrain the implementation of effective co-management.

The Lafken Mapu Lahual Multiple-Use Marine and Coastal Protected Area (LML-MUMPA), located in Osorno Province in southern Chile, illustrates these ecological and management challenges. Conservation objectives coexist with long-standing traditions of marine resource use by Mapuche-Huilliche communities and artisanal fishing associations (Bustamante et al. 2007; UNEP 2017; Oyarzo-Miranda et al. 2023). Brown macroalgae such as *Lessonia spicata*, *Lessonia trabeculata*, *Macrocystis pyrifera*, and *Durvillaea incurvata* dominate intertidal and subtidal habitats, structuring rocky coastal ecosystems and supporting diverse macrofaunal assemblages (Westermeyer et al. 2017; Wood et al. 2019; Campos et al. 2021). These meadows also sustain livelihoods through artisanal harvesting and other coastal activities (Cárcamo et al. 2014; Márquez-Porras and Vásquez 2020).

Despite its designation as a multiple-use protected area, LML-MUMPA has experienced persistent monitoring and implementation limitations, including gaps in landing data, the absence of standardized ecological protocols, and a growing number of inactive benthic management areas (Bustamante et al. 2007; Oyarzo-Miranda et al. 2023). Earlier governance arrangements were also characterized by institutional fragmentation and limited operational capacity, while participatory structures did not always provide equivalent representation to the different groups using marine resources (Serra 2012). These limitations are consistent with broader challenges reported for Chilean MUMPAs, where legal designation has not necessarily been accompanied by the operational monitoring and

adaptive-management capacity required for effective implementation (Montiel-San Martin 2020; Lynham et al. 2020).

Ecological indicators provide a practical means of addressing part of this implementation gap by translating environmental and biological variation into information that can support management decisions (Dufrene and Legendre 1997; Polanía 2010; Dávila et al. 2025). In kelp-dominated systems, canopy cover, population size structure, holdfast morphology, and associated faunal assemblages can provide information on recruitment, habitat condition, disturbance, and harvesting pressure (Antezana et al. 2006; Vásquez et al. 2012; Morris et al. 2020). However, ecological indicators become operationally useful only when they can be monitored consistently, interpreted in relation to meaningful thresholds, and connected to feasible management responses.

Participatory monitoring offers one mechanism for strengthening this connection. Local ecological knowledge can complement scientific surveys by providing observations across spatial and temporal scales that are difficult to capture through periodic field campaigns, while scientific monitoring provides standardized measurements and quantitative baselines. Integrating these knowledge systems from the design stage can therefore improve both the ecological relevance and practical feasibility of monitoring frameworks (Berkes 2004; Gelcich et al. 2010; Pita et al. 2020; Boubekri et al. 2022; Earp et al. 2022; Silva-Avila et al. 2025). Within this context, knowledge co-production refers to the joint development of indicators, thresholds, and monitoring protocols by scientists, resource users, Indigenous communities, and management institutions rather than consultation after monitoring objectives have already been defined.

Such integration is particularly relevant to adaptive management, which requires feedback between ecological change, monitoring, stakeholder learning, and management responses (Walker et al. 2004; Folke et al. 2005; Olsson et al. 2008; Cinner et al. 2016). Monitoring frameworks that remain disconnected from decision-making may generate valuable ecological information without providing mechanisms through which observed changes can trigger management responses (Kobluk et al. 2021; Banikoi et al. 2023). Co-produced monitoring may help bridge this gap by combining ecologically informative indicators with the knowledge and operational experience of the communities and institutions responsible for resource use and management.

This study develops and evaluates a participatory ecological monitoring framework for brown-algae meadows within LML-MUMPA by integrating spatial ecological surveys, long-term landing records, and structured stakeholder engagement. We assessed spatial variation in kelp population structure, holdfast morphology, and associated biodiversity across sampling units differing in environmental exposure and harvesting intensity, and examined how these ecological patterns could inform operational indicators for long-term monitoring. We hypothesized that intertidal meadows in more exposed and intensively harvested sectors would exhibit reduced density and smaller size structure, and that *D. incurvata* would show greater density and holdfast development on stable rocky substrates under lower anthropogenic pressure. We further evaluated whether participatory co-design could complement expert-derived indicators by incorporating locally relevant ecological information and improving the operational feasibility of monitoring protocols. By linking ecological condition, extraction history, and knowledge co-production, the study examines

how participatory ecological monitoring can support adaptive management of kelp-dominated ecosystems in multiple-use marine protected areas.

Materials and Methods

Study system and governance context

The Lafken Mapu Lahual Multiple-Use Marine and Coastal Protected Area (LML-MUMPA) encompasses approximately 4,463 ha along the Pacific coast of southern Chile, within Osorno Province in the Los Lagos Region. The protected area extends along a 32 km coastal corridor from San Juan de la Costa to the commune of Purranque (Fig. 1), with a marine component reaching one nautical mile offshore and a terrestrial strip comprising sea cliffs, sandy beaches, coastal bars, and marine terraces extending up to 80 m inland from the highest tide line. Freshwater inputs from the Huellehue and Cholguaco Rivers extend nearly 1,500 m seaward and contribute to the environmental conditions supporting extensive macroalgal meadows dominated by *Macrocystis pyrifera*, *Lessonia trabeculata*, and *Durvillaea incurvata*. Oceanographic conditions are characterized by temperate waters, salinity consistently above 30, a seasonal thermocline, and a tidal range of approximately 2 m, supporting high biological productivity and diverse benthic assemblages (Soto et al. 2006; MMA 2019).

LML-MUMPA combines biodiversity conservation with artisanal resource use and long-standing Indigenous cultural practices. Five Management and Exploitation Areas for Benthic Resources (MEABRs), the Chilean system of territorial use rights in fisheries (TURFs), operate within the protected area, while Mapuche-Huilliche communities maintain long-standing traditions of marine resource use throughout the coastal corridor.

This study focuses on Conservation Object 3 of the official Management Plan (MMA 2019): brown-algae meadows composed of *Macrocystis* spp., *Lessonia* spp., and *Durvillaea incurvata*, together with their associated biodiversity. These meadows structure intertidal and subtidal habitats, support diverse macrofaunal and fish assemblages, sustain artisanal fisheries, and contribute to the cultural practices of Mapuche-Huilliche communities. The Management Plan identifies uncontrolled macroalgal extraction as one of the principal threats to benthic ecosystems within the protected area (SERNAPESCA 2024).

The governance context of LML-MUMPA was considered in the design of the participatory monitoring framework. Previous socio-cultural assessments documented reliance on short-term project structures, limited continuity of funding, and weak inter-agency coordination during the early implementation of the protected area (Serra 2012). Administrative responsibilities were distributed among CONAMA, SERNAPESCA, the Chilean Navy, municipal governments, and community organizations, while participatory arrangements provided unequal representation among groups involved in marine resource use. LML-MUMPA was formally established in 2005 through Supreme Decree No. 517/2005 but operated without an approved management plan until 2019 (Resolution Ex. No. 1679/2019, MMA). This institutional context informed the development of a monitoring approach that combined ecological assessment with stakeholder participation.

Ecological sampling design and field characterization

Field campaigns were conducted during four periods in 2014 and 2015 (3–6 September, 26–28 September, 17–24 November, and 12–15 January) to characterize the spatial distribution and ecological condition of brown-algae meadows across LML-MUMPA.

Because terrestrial access was limited and coastal exposure varied considerably along the shoreline, field operations were conducted from the 8.2 m artisanal vessel Halcón II, in collaboration with local fishers who provided navigational knowledge of the coastline. Three Spatial Sampling Units (SSUs) were established along the protected area: SSU 1 in the northern sector, SSU 2 in the central sector, and SSU 3 in the southern sector (Fig. 2). The SSUs differed in wave exposure, prevailing wind conditions, substrate composition, and diving accessibility. A power analysis indicated that 25 quadrats per SSU provided >80% statistical power to detect differences of at least 20% in algal cover. Coordinates for all sampling points were recorded using a Garmin GPSMAP 76CX with a horizontal accuracy of approximately ± 5 m, and differential post-processing correction was applied to improve positional precision. The same reference points were revisited during successive campaigns to maintain spatial consistency.

At each site, 15–20 m transects were deployed perpendicular to the coastline following standardized compass bearings, with 1 m² quadrats positioned at 5 m intervals. Within each quadrat, percentage cover, density (individuals m⁻²), and holdfast diameter (cm) were recorded for the dominant intertidal canopy-forming species, *Lessonia spicata* and *Durvillaea incurvata*. Substrate composition was classified following the modified Wentworth-Udden granulometric scale (Pettijohn 1963) into four categories: boulders (>256 mm), cobbles (64–256 mm), pebbles (4–64 mm), and continuous rock platforms. Substrate composition was determined from 30 random point counts along 10 m mixed-substrate transects within each SSU. Subtidal species, including *Macrocystis pyrifera* and *Lessonia trabeculata*, were assessed using underwater video surveys. Visual fish censuses were conducted along 15 m transects, with three replicate counts per transect. These

observations were complemented with reference information from previous benthic studies conducted in the area (Jara 2002; Molinet et al. 2009; Rivas 2010; Molinet et al. 2023).

Individual algal biomass was estimated using species-specific allometric models developed by the Instituto de Fomento Pesquero (IFOP) through national monitoring programmes and applied to the Chilean coast (IFOP 2002, 2014, 2017). The models relate holdfast diameter (D, cm) to wet biomass (W, kg):

$$D. incurvata: W = e^{(-6.16 + 2.73 \ln D)}$$

$$L. spicata: W = e^{(-5.981 + 2.63 \ln D)}$$

$$M. pyrifera: W = e^{(-3.152 + 1.457 \ln D)}$$

Total biomass per quadrat (kg m^{-2}) was estimated by summing individual biomass values, and the mean and standard deviation were calculated for each SSU to characterize spatial variation in standing stock.

Macrofaunal assemblages associated with brown-algae holdfasts were characterized using fixation discs as sampling units. During each campaign, five replicate discs were collected per SSU and immediately preserved in 70% ethanol. In the laboratory, each disc was cleaned, weighed, and measured before faunal extraction under a LEICA S6D stereomicroscope equipped with LEICA KL 300 LED illumination. Specimens were counted, identified to the lowest possible taxonomic level using regional identification guides (Lancellotti and Vásquez 2000; Vásquez et al. 2001), and weighed using a SCALTEC analytical balance (precision 0.0001 g). Macrofaunal density and biomass were standardized by fixation-disc weight as follows:

$$\text{Density (ind/g)} = N / W_d \times 100$$

$$\text{Biomass index (mg/g)} = W_i / W_d \times 1000$$

where N is the total number of individuals, W_i is the total macrofaunal biomass (mg), and W_d is the dry weight (g) of each fixation disc.

Spatial differences in holdfast morphology and associated macrofaunal assemblages among SSUs were evaluated using the Kruskal–Wallis test. When significant differences were detected, Dunn's post-hoc test with Holm adjustment for multiple comparisons was applied. Community similarity was quantified using the Jaccard index (J) for presence–absence data and the Czekanowski index (C) for abundance data (Schubert and Telcs 2014), providing complementary measures of assemblage similarity among SSUs. All analyses were performed in STATISTICA v13 using a significance level of $\alpha = 0.05$.

Participatory co-design of the monitoring framework

The monitoring framework was developed through a structured co-design process integrating ecological field data with local ecological knowledge. The DPSIR model (Drivers, Pressures, State, Impacts, Responses) was used as an organizational framework to link human activities, ecological condition, and potential management responses (Delgado et al. 2022). Following the 2014–2015 field characterization, a two-day workshop was held in March 2015 with 35 participants representing five artisanal fishing associations from Mansa Bay, SERNAPESCA, the Ministry of the Environment, academic researchers, and regional NGOs (Supplementary Table S1). The workshop combined participatory mapping using high-resolution basemaps, facilitated group discussions, and indicator-validation matrices to evaluate ecological relevance and practical applicability.

Candidate bioindicators were evaluated using a multi-criteria approach based on four dimensions: detectability by fishers without specialized equipment, sensitivity to harvesting

pressure, cultural and economic relevance, and consistency with existing MEABR management plans. An initial list of candidate indicators was compiled from the scientific literature and complemented with local ecological knowledge contributed by workshop participants (Table 5). Indicators from both sources were subsequently assessed using the same criteria, allowing ecological sensitivity, local relevance, and monitoring feasibility to be considered jointly during the selection process.

Five operational indicators were selected from the candidate list through the multi-criteria assessment and incorporated into the monitoring framework, as summarized in the sensitivity and detectability matrix (Table 7). Participants from Mansa Bay, Huelleshue Cove, and C ndor Cove contributed observations on extraction dynamics and perceived ecological changes over multiple decades, which were considered alongside field observations and scientific evidence during indicator selection. The resulting adaptive-management logic model (Fig. 4) organizes the selected indicators within a sequential decision framework linking ecological threshold assessment, management triggers, potential responses, and subsequent evaluation.

Extraction trend analysis and implementation cost estimation

To provide temporal context for the ecological patterns observed within LML-MUMPA, official SERNAPESCA landing records from Mansa Bay covering the period 2000–2024 were analyzed. Because this landing site aggregates resources harvested both within and adjacent to the protected area, the records were interpreted as a regional proxy for temporal variation in extraction rather than as a direct measure of harvesting pressure within LML-MUMPA. Landing trajectories were examined to identify broad temporal phases of

resource extraction and to place the 2014–2015 ecological sampling period within the longer-term history of resource use in the area.

Implementation costs for the proposed monitoring framework were estimated through iterative budgeting sessions with fisher associations from Mansa Bay, considering shared-equipment strategies, seasonal labor availability, and the principal operational requirements of field and laboratory activities. Two implementation scenarios were evaluated. The community-led scenario assumed direct collaboration with artisanal fishers providing vessel access, local knowledge, and field assistance, resulting in an estimated annual budget of approximately USD 70,000. This scenario included fisher stipends, equipment maintenance, coordination, laboratory processing, taxonomic identification, data management, and annual reporting. The institution-led scenario assumed implementation through academic or research partnerships requiring vessel leasing, specialized diving teams, and technical personnel, with an estimated annual cost of approximately USD 100,000. Personnel represented the largest budget component under both scenarios. In the community-led scenario, fisher stipends were estimated using average fishing income for 20 field days per year distributed across two seasonal campaigns, whereas the institution-led scenario included personnel costs equivalent to 25% full-time positions for field technicians and research assistants.

Results

Spatial structure of brown-algae meadows

Brown-algae meadows and their associated fauna were surveyed during four field campaigns conducted in collaboration with artisanal fishers across the three Spatial Sampling Units. The first campaign (3–6 September 2014) provided an initial

characterization of ecological conditions and identified priority sampling sectors. The second (26–28 September 2014) expanded spatial coverage to include C ndor Cove and incorporated population assessments of *Lessonia spicata*, *Durvillaea incurvata*, and *Macrocystis pyrifera*. The third (17–24 November 2014) extended macroalgal sampling in C ndor Cove and provided additional observations of previously surveyed sectors. The fourth (12–15 January 2015) focused on intertidal assemblages of *L. spicata* and *D. incurvata* and documented additional brown and red algal taxa, including *Lessonia trabeculata* and *Mesophyllum* sp., at depths >10 m. SSU 1 comprised intertidal meadows dominated by *L. spicata* and *D. incurvata*; SSU 2 included a subtidal meadow of *L. trabeculata*, recorded during repeated sampling; and SSU 3 supported the broadest assemblage, with all four target macroalgal species recorded and georeferenced.

Intertidal meadows across SSUs 1, 2, and 3 were predominantly associated with continuous rocky substrates. *Durvillaea incurvata* was the most abundant species, with higher densities in SSUs 1 and 2. More than 95% of individuals had holdfast diameters <21 cm. The 0–3 cm size class was dominant in SSUs 1 and 2, whereas individuals between 3 and 6 cm predominated in SSU 3. *Lessonia spicata* occurred in all three SSUs and reached its highest abundance in SSU 1; more than 90% of individuals also had holdfast diameters <21 cm. Size distributions differed among SSUs, with the 3–6 cm class most frequent in SSU 1, the 0–3 cm class in SSU 2, and the 3–6 cm class in SSU 3. *Macrocystis pyrifera* had a more restricted distribution, occurring only in SSUs 2 and 3 and at substantially lower abundances; in SSU 3, nearly three quarters of individuals occurred within the 3–6 and 6–9 cm size classes. Overall, the sampled meadows were characterized by a predominance of small size classes, together with spatial differences in population structure among SSUs.

The spatial variation in population size structure, holdfast morphometry, and associated macrofaunal richness is summarized in figure 5.

Faunal assemblages and bathymetric patterns

Herbivorous consumers were scarce across the surveyed meadows. The commercially important sea urchin *Loxechinus albus* was uncommon in intertidal habitats, while *Concholepas concholepas* was not recorded at the sampled sites. Sea stars were the most frequently observed group of mobile invertebrates, whereas limpets showed low representation. Overall, the surveys indicated low occurrence of several herbivorous and predatory taxa within the sampled intertidal habitats.

Underwater video surveys showed a distinct bathymetric distribution of the dominant brown algae. Intertidal rocky platforms were characterized primarily by *L. spicata* and *D. incurvata*, whereas *L. trabeculata* occurred in subtidal habitats at depths >10 m. Available information on harvesting activities indicated corresponding differences in resource use, with *L. trabeculata* harvested primarily from subtidal areas and *D. incurvata* collected seasonally from accessible intertidal habitats. The spatial distribution of these assemblages across SSUs is shown in figures 6 and 7.

Visual fish censuses conducted within the algal habitat recorded three species in SSUs 2 and 3: *Calliclinus geniguttatus*, *Patagonotothen tessellata*, and *Isacia conceptionis*. Surveys were conducted between 14:00 and 15:00 h, which limited the temporal coverage of the fish assessment. Consequently, the recorded species richness should be interpreted as a characterization of the assemblage observed during the survey period rather than as a comprehensive estimate of fish diversity.

Biodiversity associated with kelp holdfasts

Fixation-disc assessments across the three SSUs documented 17 taxa belonging to six phyla (Table 1). Gastropods such as *Scurria scurra* and *Crepidatella dilatata* were among the recorded taxa, together with the commercially important gastropod *Concholepas concholepas*. Morphometric comparisons of *Durvillaea incurvata* holdfasts showed spatial variability in both diameter and weight, but differences among SSUs were not statistically significant (Fig. 8a–b). Mean holdfast diameter was 17.2 ± 3.3 cm in SSU 1, 19.1 ± 4.5 cm in SSU 2, and 16.3 ± 4.6 cm in SSU 3 (Kruskal–Wallis, $H = 2.10$, $P = 0.350$). Mean holdfast weight was 416.6 ± 185.9 g, 568.1 ± 338.5 g, and 739.6 ± 658.4 g, respectively, with no significant differences among SSUs ($H = 1.07$, $P = 0.586$).

Macrofaunal assemblages associated with *D. incurvata* holdfasts showed contrasting spatial patterns (Fig. 8c; Table 2). Cumulative taxonomic richness was highest in SSU 3, whereas mean richness per holdfast did not differ significantly among SSUs (Kruskal–Wallis, $H = 5.33$, $p\text{-value} = 0.070$). Faunal density differed significantly among SSUs ($H = 6.32$, $P = 0.042$), with post-hoc comparisons indicating significantly higher density in SSU 2 than in SSU 3 (Dunn's test with Holm adjustment, $P = 0.049$). Mean faunal biomass was highest in SSU 2, although differences among SSUs were not statistically significant ($H = 3.62$, $P = 0.164$). Overall, holdfast morphology and associated macrofaunal assemblages did not follow a single spatial gradient: SSU 3 supported the highest cumulative taxonomic richness, whereas SSU 2 showed the highest mean faunal density and biomass.

Extraction trajectory and temporal phases

SERNAPESCA landing records from Mansa Bay for 2000–2024 showed a fishery strongly dominated by macroalgal resources (Table 3, Fig. 9). *Durvillaea incurvata* was the dominant landed species, totaling 13,953 wet tons over the study period. Recorded landings began in 2009 and showed substantial interannual variation, with peaks in 2017 and 2018 (1,989 and 2,235 tons, respectively) and a secondary peak in 2024 (1,358 tons). *Lessonia spicata* accumulated 4,416 wet tons since 2009, with the highest annual landings recorded in 2022 (1,239 tons) and 2021 (852 tons). *Sarcothalia crispata* accounted for 4,774 wet tons, with higher landings between 2015 and 2023. Together, these three species represented more than 70% of the total biomass landed between 2000 and 2024 (SERNAPESCA 2024). Invertebrate resources were also represented in the landing records, including *Concholepas concholepas* (647 tons) and *Loxechinus albus* (694 tons).

Based on changes in the magnitude and composition of recorded landings, together with the institutional chronology of LML-MUMPA, four temporal phases were distinguished: early exploitation (2000–2008), expansion and consolidation (2009–2015), high extraction (2016–2019), and fluctuating extraction following adoption of the Management Plan (2020–2024) (Table 4). The highest macroalgal landings occurred during the period between the formal designation of LML-MUMPA in 2005 and approval of its Management Plan in 2019. The ecological surveys conducted in 2014–2015 therefore coincided with the transition between the expansion phase and the subsequent period of highest recorded macroalgal extraction. Because Mansa Bay landing records integrate catches originating both within and adjacent to LML-MUMPA, these temporal patterns provide regional

context for resource use but cannot be attributed exclusively to extraction within the protected area.

Co-produced selection of ecological indicators

Ecological field observations and local ecological knowledge contributed by artisanal fishers were integrated during the bioindicator selection process. Candidate taxa represented intertidal and subtidal rocky habitats as well as sandy coastal environments and were evaluated according to ecological sensitivity, detectability, local relevance, and their potential application in long-term monitoring. Rather than being used as independent lines of evidence, field observations and local knowledge provided complementary information for identifying taxa considered relevant to ecological condition and feasible for operational monitoring.

In rocky intertidal habitats, limpets including *Fissurella picta*, *Scurria scurra*, and *Scurria zebrina* were identified as candidate indicators based on their ecological characteristics and potential sensitivity to changes in grazing pressure, substrate conditions, and hydrodynamic exposure. *Concholepas concholepas* was also included because of its ecological and fisheries relevance and its potential responsiveness to harvesting pressure. Candidate indicators for subtidal rocky habitats included *Pagurus villosus*, *Crepidatella dilatata*, *Glycymeris ovatus*, *Fusitriton magellanicus*, and *Nassarius taeniolatus*. In sandy intertidal habitats, *Excirolana hirsuticauda* and *Orchestoidea tuberculata* were selected as potential indicators of changes in sedimentary and shoreline conditions, whereas *Goniada uncinigera* and *Euzonus* sp. were identified for subtidal sandy habitats. The macroalga *Mazzaella laminarioides* was also incorporated as an intertidal indicator because of its potential sensitivity to environmental conditions and harvesting.

Two fish species, *Calliclinus geniguttatus* and *Calliclinus nudiventris*, were incorporated as indicators for rocky coastal habitats through local ecological knowledge contributed during the participatory workshops. Neither species was included in the initial expert-derived candidate list. Their incorporation therefore expanded the original suite of candidate indicators and provided a direct example of how fisher knowledge contributed information that was not represented in the initial scientific selection. The resulting indicator suite and its associated ecological criteria, monitoring thresholds, and potential management responses are summarized in Tables 5 and 6, with the conceptual relationships presented in Fig. 3 and the sensitivity and detectability matrix in Table 7.

Discussion

The ecological patterns observed across LML-MUMPA reveal marked spatial variation in the structure of brown-algae meadows and their associated biodiversity. Northern and central sampling units were characterized by a predominance of small individuals of *Durvillaea incurvata* and *Lessonia spicata*, whereas the southern sector showed broader size distributions, larger *D. incurvata* holdfasts, and greater associated faunal richness. These differences occurred across a relatively short coastal distance and coincided with spatial variation in wave exposure, substrate characteristics, and reported harvesting intensity. Rather than indicating a single controlling factor, the observed patterns are therefore consistent with the combined influence of environmental conditions and resource use on the structure of kelp-dominated rocky habitats.

The predominance of small size classes in *D. incurvata* and *L. spicata* provides partial support for our first hypothesis that exposed and intensively harvested sectors would exhibit reduced density and smaller population structure. More than 95% of *D. incurvata*

and 90% of *L. spicata* individuals had holdfast diameters below 21 cm, while SSU 3 exhibited a broader size distribution than the northern and central sampling units. Hydrodynamic exposure can influence recruitment, survival, and adult morphology in kelp-dominated habitats, while harvesting can selectively remove larger individuals and modify population size structure (Carr et al. 2003; Pérez-Matus et al. 2017). The patterns observed in LML-MUMPA are compatible with these interacting mechanisms, although their relative contributions cannot be separated with the present observational design. This spatial heterogeneity reinforces the importance of monitoring population size structure across multiple sectors rather than relying on aggregate measures of kelp abundance or biomass, particularly where environmental gradients and harvesting activities vary over short distances (Molinet et al. 2023).

Spatial variation in *D. incurvata* holdfast morphology and associated fauna provides additional evidence of ecological heterogeneity among sampling units. Although holdfast diameter and weight varied among SSUs, these differences were not statistically significant. In contrast, holdfast-associated macrofaunal assemblages showed distinct spatial patterns. Cumulative taxonomic richness was highest in SSU 3, whereas SSU 2 showed the highest mean faunal density and biomass. Faunal density differed significantly among SSUs, with post-hoc comparisons indicating a significant difference between SSU 2 and SSU 3. These contrasting patterns indicate that holdfast morphology and associated macrofaunal assemblages did not follow a simple north–south gradient. Kelp holdfasts provide structurally complex habitats that offer attachment surfaces, refuges, and microhabitats for benthic organisms, and similar relationships between kelp structure and associated biodiversity have been reported in other exploited kelp systems (Morris et al.

2020). Overall, these findings provide partial support for our second hypothesis while suggesting that substrate conditions, hydrodynamic exposure, and harvesting history may contribute simultaneously to the spatial ecological patterns observed.

Long-term landing records provide temporal context for these ecological patterns. Macroalgal landings from Mansa Bay increased markedly after 2009 and reached their highest levels during the years surrounding the adoption of the LML-MUMPA Management Plan in 2019. These records integrate catches originating both within and adjacent to the protected area and therefore cannot reconstruct harvesting pressure at individual SSUs. Nevertheless, the ecological surveys conducted in 2014–2015 coincided with a period of expanding macroalgal extraction and preceded the highest recorded landings of *D. incurvata*. This broader extraction history highlights the value of integrating ecological monitoring with fisheries information when interpreting the condition of multiple-use coastal ecosystems.

The participatory component provides a complementary dimension to these ecological findings. Local ecological knowledge contributed by artisanal fishers expanded the initial expert-derived candidate suite through the incorporation of taxa that were not represented in the scientific selection, most notably *Calliclinus geniguttatus* and *Calliclinus nudiventris*. The participatory process therefore influenced the ecological content of the monitoring framework rather than functioning solely as a mechanism for stakeholder consultation. This finding provides partial support for our third hypothesis concerning the contribution of participatory co-design to the operational relevance of monitoring. However, whether this approach ultimately increases stakeholder acceptance, compliance, or long-term

implementation cannot be established from the present study and will require evaluation through subsequent monitoring cycles.

Interpreting ecological patterns through a social-ecological lens

The spatial heterogeneity documented across LML-MUMPA can be interpreted within a broader social-ecological context in which environmental conditions, resource use, and institutional arrangements interact. Brown-algae meadows dominated by *L. spicata*, *D. incurvata*, and *M. pyrifera* constitute a core Conservation Object under the official Management Plan (MMA 2019), while simultaneously supporting artisanal harvesting and other coastal activities. Differences among SSUs in population size structure, holdfast morphology, and associated biodiversity occurred across sectors that also differed in hydrodynamic exposure, substrate characteristics, and reported harvesting intensity. These patterns are consistent with broader evidence showing that kelp-dominated ecosystems respond to interacting physical and anthropogenic pressures (Carr et al. 2003; Halpern et al. 2010). In LML-MUMPA, however, the observational design does not allow the relative contribution of these drivers to be separated. The ecological patterns should therefore be interpreted as the outcome of multiple interacting processes rather than as direct indicators of governance performance.

Holdfast-associated assemblages illustrate this interaction particularly well. Larger *D. incurvata* holdfasts were recorded in SSU 3, which also supported the highest faunal richness, whereas SSU 2 showed the highest associated faunal density and biomass. These patterns are consistent with the habitat-forming role of structurally complex macroalgae, whose holdfasts provide refuge, attachment surfaces, and trophic resources for benthic organisms (Uribe et al. 2015; Villasante et al. 2023). At the same time, variation in holdfast

structure occurred across sectors differing in environmental exposure and reported harvesting intensity, making it difficult to attribute the observed biological differences to any single mechanism. The low occurrence of commercially important invertebrates such as *Loxechinus albus* and *Concholepas concholepas* in the intertidal surveys, despite their representation in regional landing records, further illustrates the value of considering ecological and fisheries information together, without implying a direct causal relationship between harvesting and the local patterns observed.

LML-MUMPA was formally designated in 2005 but operated without an approved Management Plan until 2019. Much of the increase in recorded macroalgal extraction occurred during this period. Although this temporal overlap does not establish a causal relationship between institutional conditions and extraction dynamics, it highlights the importance of complementing legal designation with sustained ecological monitoring and mechanisms capable of incorporating monitoring information into management decisions.

From a social-ecological perspective, this implementation gap emphasizes the importance of feedback mechanisms connecting ecological monitoring, resource users, and management institutions. Adaptive management depends not only on detecting ecological change but also on having procedures through which monitoring information can be interpreted and translated into feasible responses. The participatory framework developed here addresses this interface by combining ecological indicators with local observations and linking them to potential management actions. Its contribution therefore lies less in attributing past ecological conditions to particular governance failures than in establishing a mechanism through which future ecological information could support adaptive management.

Co-production of knowledge as a mechanism for adaptive management

A central contribution of this study is showing how knowledge co-production can contribute to ecological monitoring within a multiple-use marine protected area. The DPSIR framework provided a structure for integrating ecological field observations with local ecological knowledge, while the participatory process expanded the information considered during indicator selection. Fishers contributed observations derived from long-term experience with coastal habitats and resource use, whereas scientific surveys provided standardized measurements of spatial ecological patterns. These knowledge sources therefore operated at different but complementary spatial and temporal scales, broadening the ecological basis of the monitoring framework and connecting indicator selection with the practical experience of resource users.

The incorporation of *C. geniguttatus* and *C. nudiventris*, neither of which was included in the initial expert-derived candidate list, provides a concrete example of this contribution. Their identification through fisher knowledge demonstrates that the participatory process added ecological information that was not represented in the original scientific selection. This is consistent with studies showing that local ecological knowledge can complement conventional monitoring by providing observations across temporal and spatial scales that are difficult to capture through periodic scientific surveys (Berkes 2004; Kobluk et al. 2021; Silva-Avila et al. 2025). Co-production in this case did not replace standardized ecological assessment; rather, it expanded the information considered in designing the monitoring framework.

The relevance of this integration extends beyond indicator selection. Participatory monitoring can contribute to adaptive management by involving resource users and

management institutions in defining what is monitored, how ecological change is interpreted, and which responses may be operationally feasible. Within LML-MUMPA, the co-design process linked ecological indicators, locally derived observations, monitoring thresholds, and potential management actions within a common framework. Its principal contribution was therefore not to demonstrate improved governance outcomes, but to create a structured interface between ecological evidence, local knowledge, and management decisions. Whether these arrangements ultimately improve participation, compliance, adaptive capacity, or ecological outcomes will require evaluation through future implementation and repeated monitoring.

Comparison with international kelp monitoring frameworks

The LML-MUMPA framework shares several ecological objectives with kelp-monitoring programmes developed in other temperate regions, while differing in the way monitoring information is linked to stakeholder participation and management. Long-term programmes such as PISCO in California, monitoring of urchin-driven changes in Tasmania, and biomass assessments of *Ecklonia maxima* in South Africa illustrate the value of standardized ecological observations for detecting changes in kelp abundance, population structure, and associated communities (Carr et al. 2003; Johnson et al. 2011; Anderson et al. 2007). These approaches provide important methodological references for kelp monitoring, although their institutional settings, monitoring objectives, and levels of stakeholder participation differ from those of LML-MUMPA. The framework developed here complements such approaches by explicitly incorporating local ecological knowledge and stakeholder participation into indicator selection and the interpretation of monitoring information.

This distinction is particularly relevant for multiple-use marine protected areas, where ecological monitoring operates alongside extractive activities and involves resource users who interact directly with the monitored ecosystems. Consequently, the potentially transferable component of the LML-MUMPA framework is not a fixed set of species or sampling protocols, but an approach through which ecological indicators can be adapted to local environmental conditions, resource-use patterns, and management priorities. This may be particularly relevant where sustained institution-led monitoring is constrained by logistical or financial capacity.

The framework incorporates quantitative reference values for selected indicators, including 40% canopy cover, 6 cm holdfast diameter, and a 30% decline in epifaunal richness. These values provide an initial basis for linking ecological change with potential management responses but, because they were derived from the ecological information and participatory process available for LML-MUMPA rather than from long-term evaluation of ecosystem responses, they should be considered provisional management thresholds. The broader contribution of the framework therefore lies in combining ecological monitoring, locally derived knowledge, and explicit decision criteria within a common adaptive-management structure rather than providing a universal monitoring model.

Study limitations and future directions

Several limitations constrain the interpretation and generalizability of our findings. The 2014–2015 field surveys provide a temporal snapshot that cannot distinguish persistent spatial patterns from transient responses to environmental variability or recent disturbance. Brown-algae meadows can fluctuate substantially in response to ENSO variability, storm

events, and episodic recruitment (Pérez-Matus et al. 2017; Oyarzo-Miranda et al. 2023), and multi-year observations will therefore be necessary to evaluate the temporal stability of the ecological patterns reported here. The absence of pre-designation ecological data prevents attribution of the observed patterns to specific management interventions or their absence. In addition, landing records integrate catches originating both within and adjacent to the protected area, limiting their use for quantifying extraction pressure specifically within LML-MUMPA. Spatially explicit catch information, through vessel logbooks or GPS-based records where feasible, would improve the capacity to relate harvesting patterns to ecological conditions within individual sectors.

The proposed management thresholds also require evaluation through repeated monitoring. Longer time series would allow natural variability to be distinguished from persistent ecological change and provide an empirical basis for adjusting threshold values. Population modelling and, where feasible, targeted studies of harvesting responses could further strengthen their ecological basis. Fish assemblage characterization was also constrained by the limited temporal coverage of visual censuses, conducted between 14:00 and 15:00 h. Future surveys should incorporate observations across different periods of the day, including dawn and dusk and, where logistically feasible, nocturnal sampling, to better characterize temporal variation in fish assemblages (Pérez-Matus et al. 2012).

Finally, although the participatory process incorporated artisanal fishers, government agencies, researchers, NGOs, and Mapuche-Huilliche representatives, participation was not equally distributed among stakeholder groups. Indigenous authorities were underrepresented relative to their cultural significance and long-standing relationship with

marine resources in the area, while informal harvesters and emerging tourism operators were largely absent from the workshops. Future iterations should seek broader representation of these groups and combine repeated participatory evaluation with ecological monitoring to assess stakeholder engagement, operational feasibility, and the incorporation of monitoring information into management decisions over time.

Implications for monitoring and adaptive management

The monitoring framework developed for LML-MUMPA illustrates how ecological observations, local ecological knowledge, and explicit decision criteria can be integrated to support adaptive management in multiple-use marine protected areas. Its application requires continuity in ecological monitoring, sustained stakeholder participation, and institutional mechanisms capable of translating observed changes into management responses. The two implementation scenarios evaluated here, with estimated annual costs of approximately USD 70,000 for a community-integrated model and USD 100,000 for an institution-led model, provide context-specific estimates of the resources required to maintain such a programme rather than evidence of economic feasibility across other protected areas.

Explicit ecological indicators and provisional management thresholds provide a potential mechanism for connecting monitoring results with management decisions. Their application should remain adaptive, with repeated observations used to distinguish natural variability from persistent change and refine threshold values before they become formal decision rules. This approach could be adapted to other multiple-use coastal protected areas

and benthic management systems, provided that indicator selection and threshold definition account for local ecological conditions, resource-use patterns, and management objectives.

Scaling participatory monitoring beyond LML-MUMPA would also require attention to the social and institutional conditions under which co-production occurs. The process described here benefited from established relationships among researchers, artisanal fisher organizations, community representatives, and public institutions in the Mansa Bay area. Similar approaches elsewhere would require sufficient time for stakeholder engagement, appropriate technical support, and continuity beyond short-term project cycles. Rather than prescribing a single institutional model, the LML-MUMPA experience suggests that effective implementation depends on maintaining connections among ecological monitoring, local knowledge, stakeholder deliberation, and management capacity.

More broadly, ecological monitoring becomes operationally meaningful when information can be evaluated against transparent criteria and incorporated into management processes. Future implementation of the LML-MUMPA framework will provide an opportunity to determine whether the proposed indicators and thresholds reliably detect ecologically meaningful change, whether the community-integrated monitoring model can be sustained over time, and whether monitoring results are effectively incorporated into management decisions.

Conclusion

This study developed a participatory ecological monitoring framework for brown-algae meadows in the Lafken Mapu Lahual Multiple-Use Marine and Coastal Protected Area by integrating spatial ecological surveys, long-term landing records, and local ecological

knowledge. The ecological assessment revealed marked spatial heterogeneity in kelp population structure and associated biodiversity, whereas differences in *D. incurvata* holdfast morphology among sampling units were not statistically significant. *Durvillaea incurvata* and *Lessonia spicata* were dominated by small size classes, while holdfast-associated macrofaunal assemblages showed contrasting spatial patterns, with the southern sampling unit supporting the highest cumulative taxonomic richness and the central sampling unit showing the highest mean faunal density and biomass. These patterns occurred across sectors differing in environmental exposure, substrate characteristics, and reported harvesting intensity, emphasizing the need for spatially explicit monitoring of kelp-dominated coastal ecosystems.

Landing records from 2000 to 2024 placed these ecological observations within a broader trajectory of changing resource use, including substantial increases in macroalgal extraction after 2009. Although these records cannot resolve harvesting pressure specifically within LML-MUMPA, they demonstrate the importance of combining ecological observations with longer-term fisheries information when interpreting the condition of multiple-use coastal ecosystems. The absence of pre-designation ecological data and the limited temporal coverage of field surveys prevent causal attribution of the observed ecological patterns to harvesting or management history, but also highlight the importance of establishing sustained monitoring capable of detecting future change.

Knowledge co-production contributed directly to the design of this monitoring framework. The participatory process expanded the initial expert-derived indicator suite through the incorporation of locally identified taxa, including *Calliclinus geniguttatus* and *Calliclinus nudiventris*, demonstrating that fisher knowledge contributed ecological information not

represented in the original scientific selection. The resulting framework links ecological indicators with provisional quantitative thresholds and potential management responses, providing a structured basis for adaptive monitoring while recognizing that threshold performance requires evaluation through repeated observations.

The broader contribution of the LML-MUMPA case lies in showing how standardized ecological assessment, fisheries information, and local ecological knowledge can be combined within a common monitoring framework for a multiple-use marine protected area. Rather than providing a universal model or demonstrating governance outcomes that have yet to be evaluated, the framework offers an adaptable approach for connecting ecological evidence with stakeholder knowledge and management processes. Long-term implementation will be necessary to determine whether this integration improves the detection of ecological change and the incorporation of monitoring information into management decisions. In this sense, effective adaptive management depends not only on generating ecological information, but on maintaining the institutional and participatory processes through which that information can inform action.

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Author Contributions

P.M.R. contributed to the conceptualization, methodology, formal analysis, data interpretation, visualization, and writing of the original manuscript. S.S. contributed to data curation, preparation and review of tables, updating the fisheries landing dataset, preparation of the corresponding figure, and review and editing of the manuscript. Both authors reviewed and approved the final version of the manuscript.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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Legend tables

Table 1.- Taxonomic composition of macroinvertebrates associated with natural holdfasts of *Lessonia spicata*, *Durvillaea incurvata*, and *Lessonia trabeculata* across the three Spatial Sampling Units (SSUs) of LML-MUMPA. Taxa were identified to the lowest possible taxonomic level using stereomicroscopy (Leica S6D). A total of 17 taxa belonging to six phyla were documented across all SSUs, with cumulative taxonomic richness increasing from SSU 1 (9 taxa) to SSU 3 (12 taxa). Presence-absence patterns illustrate spatial variation in holdfast-associated benthic assemblages across LML-MUMPA.

Phylum	Class	Scientific name
Mollusca	Gastropoda	<i>Scurria scurra</i> (Lesson 1831)
		<i>Crepidatella dilatata</i> (Lamarck 1822)
		<i>Fisurella</i> sp. (Bruguiere 1787)
		<i>Concholepas concholepas</i> (Martyn 1784)
		<i>Prisogaster niger</i> (Wood 1828)
	Peleicypoda	<i>Semimytilus algosus</i> (Gould 1850)
Antropoda	Crustacea	<i>Aulacomya atra</i> (Molina 1782)
		<i>Chiton cumingsi</i> (Frembly 1827)
		<i>Allopetrolisthes punctatus</i> (Guérin 1835)
	Amphipoda	<i>Petrolisthes violaceus</i> (Guérin 1829)
		<i>Petrolisthes tuberculatus</i> (Guérin 1835)
Echinodermata	Asteroidea	<i>Stichaster straitus</i> (Müller and Troschel 1840)
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i> (Lesson 1830)
Annelida	Polichaeta	<i>Phragamatopoma moerchi</i> (Kinberg 1866)
		<i>Nereis</i> sp. (Linnaeus 1758)
Porifera	Demospongiae	

1011 Table 2.- Density (ind/g) and biomass (mg/g) of macroinvertebrate assemblages associated with fixation discs of *D. incurvata*, *L.*
1012 *spicata* and *L. trabeculata* in SSU 1, SSU 2 and SSU 3. Density values represent individuals normalized by disc wet weight; biomass
1013 reflects individual wet weight relative to disc weight. n = 5 natural discs per species per SSU. Empty cells indicate taxon absence. SSU
1014 2 showed highest faunal density and SSU 3 the highest species richness per disc.

			SSU1 – <i>Durvillaea incurvata</i>									
			Disc1		Disc2		Disc3		Disc4		Disc5	
Phylum	Class	Scientific name	Density	Biomass	Density	Biomass	Density	Biomass	Density	Biomass	Density	Biomass
Mollusca	Gastropoda	<i>Scurria scurra</i>	3.06	8.29			2.05	12.93			0.55	0.22
		<i>Crepidatella dilatata</i>										
		<i>Fisurella</i> sp.										
		<i>Concholepas concholepas</i>										
		<i>Prisogaster niger</i>										
	Pelecypoda	<i>Semipylus albosus</i>							0.44	0.01		
		<i>Aulacomya atra</i>										
	Poliplacophora	<i>Chiton cumingsi</i>										
	Crustacea	<i>Allopetrolisthes punctatus</i>										
		<i>Petrolisthes violaceus</i>										
		<i>Petrolisthes tuberculatus</i>					0.45	32.79				
	Amphipoda		0.56	0.24			3.41	0.25			2.47	0.08
Echinodermata	Asteroidea	<i>Stichaster straitus</i>										
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i>										
Annelida	Polichaeta	<i>Phragmatopoma moerchi</i>	0.28	0.27					0.44	0.25	0.27	0.20
		<i>Nereis</i> sp.										
Porifera	Demospongiae											

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1017 Continuation: Table 2.

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			SSU1 – <i>Lessonia spicata</i>									
			Disc1		Disc2		Disc3		Disc4		Disc5	
Phylum	Class	Scientific name	Density	Biomass	Density	Density	Biomass	Density	Biomass	Density	Density	Biomass
Mollusca	Gastropoda	<i>Scurria scurra</i>			0.06	0.96					0.12	0.48
		<i>Crepidatella dilatata</i>										
		<i>Fisurella</i> sp.										
		<i>Concholepas concholepas</i>										
		<i>Prisogaster niger</i>	0.07	8.23	0.06	0.78						
	Peleicypoda	<i>Semipylus alga</i>	0.03	0.05	0.06	0.04			0.17	0.03		
		<i>Aulacomya atra</i>										
	Poliplacophora	<i>Chiton cumingsi</i>									0.12	11.84
Arthropoda	Crustacea	<i>Allopetrolisthes punctatus</i>			0.06	0.31						
		<i>Petrolisthes violaceus</i>									0.12	6.36
		<i>Petrolisthes tuberculatus</i>										
	Amphipoda		0.03	0.01	0.13	0.01						
Echinodermata	Asteroidea	<i>Stichaster straitus</i>										
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i>										
Annelida	Polichaeta	<i>Phragmatopoma moerchi</i>					0.06	0.01				
		<i>Nereis</i> sp.										
Porifera	Demospongiae											

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1023 Continuation: Table 2.

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			SSU2 – <i>Durvillaea incurvata</i>									
			Disc1		Disc2		Disc3		Disc4		Disc5	
Phyllum	Class	Scientific name	Density	Biomass	Density	Density	Biomass	Density	Biomass	Density	Density	Biomass
Mollusca	Gastropoda	<i>Scurria scurra</i>	1.17	19.52	2.71	2.27	5.46	31.18	1.31	14.67	2.06	15.20
		<i>Crepidatella dilatata</i>										
		<i>Fisurella</i> sp.										
		<i>Concholepas concholepas</i>										
		<i>Prisogaster niger</i>										
	Peleicypoda	<i>Semipylus algaosus</i>	8.28	0.44			9.61	10.87	0.27	0.34	0.31	0.14
		<i>Aulacomya atra</i>										
	Poliplacophora	<i>Chiton cumingsi</i>										
	Arthropoda	<i>Allopetrolisthes punctatus</i>										
		<i>Petrolisthes violaceus</i>										
		<i>Petrolisthes tuberculatus</i>			0.40	29.97			0.15	10.70	0.15	4.95
	Amphipoda		4.34	0.33	2.80	0.12	1.84	0.50	11.56	2.46	0.77	0.16
Echinodermata	Asteroidea	<i>Stichaster straitus</i>										
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i>										
Annelida	Polichaeta	<i>Phragmatopoma moerchi</i>							4.48	0.39		
		<i>Nereis</i> sp.			0.38	0.40	0.41	0.79				
Porifera	Demospongiae											

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1029 Continuation: Table 2.

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			SSU2 – <i>Lessonia trabeculata</i>									
			Disc1		Disc2		Disc3		Disc4		Disc5	
Phylum	Class	Scientific name	Density	Biomass	Density	Density	Biomass	Density	Biomass	Density	Density	Biomass
Mollusca	Gastropoda	<i>Scurria scurra</i>										
		<i>Crepidatella dilatata</i>										
		<i>Fisurella</i> sp.										
		<i>Concholepas concholepas</i>										
		<i>Prisogaster niger</i>										
	Peleicypoda	<i>Semipylus albosus</i>										
		<i>Aulacomya atra</i>					0.53	1.13			1.09	3.17
	Poliplacophora	<i>Chiton cumingsi</i>									0.27	3.76
Arthropoda	Crustacea	<i>Allopetrolisthes punctatus</i>										
		<i>Petrolisthes violaceus</i>										
		<i>Petrolisthes tuberculatus</i>										
	Amphipoda											
Echinodermata	Asteroidea	<i>Stichaster straitus</i>					0.06	7.10				
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i>										
Annelida	Polichaeta	<i>Phragmatopoma moerchi</i>					0.12	0.02				
		<i>Nereis</i> sp.	0.77	0.25								
Porifera	Demospongiae								0.10	1.94		

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1035 Continuation: Table 2.

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			SSU3 – <i>Durvillaea incurvata</i>									
			Disc1		Disc2		Disc3		Disc4		Disc5	
Phylum	Class	Scientific name	Density	Biomass	Density	Density	Biomass	Density	Biomass	Density	Density	Biomass
Mollusca	Gastropoda	<i>Scurria scurra</i>										
		<i>Crepidatella dilatata</i>										
		<i>Fisurella</i> sp.							0.22	0.09		
		<i>Concholepas concholepas</i>					0.23	13.61				
		<i>Prisogaster niger</i>							0.22	0.37		
	Peleicypoda	<i>Semipylus algaesus</i>			0.05	0.07	0.45	2.55	7.35	44.60		
		<i>Aulacomya atra</i>										
	Poliplacophora	<i>Chiton cumingsi</i>							0.45	3.52		
Arthropoda	Crustacea	<i>Allopetrolisthes punctatus</i>										
		<i>Petrolisthes violaceus</i>										
		<i>Petrolisthes tuberculatus</i>			0.05	3.16						
	Amphipoda								0.22	0.12		
Echinodermata	Asteroidea	<i>Stichaster straitus</i>										
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i>										
Annelida	Polichaeta	<i>Phragmatopoma moerchi</i>							0.22	0.03	0.43	0.05
		<i>Nereis</i> sp.	0.29	0.59					0.45	1.85		
Porifera	Demospongiae											

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1041 Continuation: Table 2.

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			SSU3 – <i>Lessonia trabeculata</i>									
			Disc1		Disc2		Disc3		Disc4		Disc5	
Phylum	Class	Scientific name	Density	Biomass	Density	Density	Biomass	Density	Biomass	Density	Density	Biomass
Mollusca	Gastropoda	<i>Scurria scurra</i>										
		<i>Crepidatella dilatata</i>					0.24	0.29				
		<i>Fisurella</i> sp.										
		<i>Concholepas concholepas</i>										
		<i>Prisogaster niger</i>										
	Peleicypoda	<i>Semipylus albosus</i>										
		<i>Aulacomya atra</i>			0.25	2.79						
	Poliplacophora	<i>Chiton cumingsi</i>			0.25	2.04						
Arthropoda	Crustacea	<i>Allopetrolisthes punctatus</i>										
		<i>Petrolisthes violaceus</i>										
		<i>Petrolisthes tuberculatus</i>										
	Amphipoda						0.24	0.04				
Echinodermata	Asteroidea	<i>Stichaster straitus</i>										
Coelenterata	Anthozoa	<i>Anthothoe chilensis</i>			2.76	14.19	0.24	1.28				
Annelida	Polichaeta	<i>Phragmatopoma moerchi</i>	2.31	0.53								
		<i>Nereis</i> sp.	0.23	1.32								
Porifera	Demospongiae											

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1047 Table 3.- Official landings recorded at Mansa Bay (2000–2024), expressed in wet tons, integrating extraction from within and adjacent
1048 to LML-MUMPA. Values represent the most reliable long-term indicator of regional exploitation pressure. Dominant resources
1049 include *Durvillaea incurvata* (13,953 tons), *Sarcothalia crispata* (4,774 tons) and *Lessonia spicata* (4,416 tons), collectively exceeding
1050 70% of total biomass landed. Source: SERNAPESCA official statistics (updated to 2024).

Group	Scientific name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Macroalgae	<i>Chondracanthus chamissoi</i>	11												
	<i>Durvillaea incurvata</i>										144	865	866	80
	<i>Macrocystis pyrifera</i>													
	<i>Lessonia spicata</i>													
	<i>Lessonia trabeculata</i>													
	<i>Pyropia sp.</i>												1	
	<i>Mazzaella laminarioides</i>												18	5
	<i>Sarcothalia crispata</i>										4		204	313
	<i>Sarcopeltis skottsbergii</i>												27	1
Fish	<i>Dissostichus eleginoides</i>													
	<i>Genypterus chilensis</i>	1	2							3				1
	<i>Genypterus blacodes</i>	9	1											
	<i>Genypterus maculatus</i>	16	3											
	<i>Cilus gilberti</i>		32										2	
	<i>Merluccius gayi gayi</i>													
	<i>Merluccius australis</i>		110											13
	<i>Callorhynchus callorhynchus</i>	8	3							1			1	
	<i>Odontesthes regia</i>													
	<i>Psammobatis sp.</i>	236	3											
	<i>Zearaja chilensis</i>			24	12	3	4			27	3		37	
	<i>Brama australis</i>		110											
	<i>Sprattus fuegensis</i>													2
	<i>Thyrstites atun</i>								2	2		1	8	147
Mollusks	<i>Venus antiqua</i>													1
	<i>Aulacomya atra</i>		4											1
	<i>Mytilus chilensis</i>	2	12											
	<i>Fissurella sp.</i>	89										9	2	
	<i>Fissurella nigra</i>													1
	<i>Concholepas concholepas</i>	36					115	45	97	44	21	32	11	11
Crustaceans	<i>Dosidicus gigas</i>													
	<i>Lithodes santolla</i>													9
Other	<i>Metacarcinus edwardsi</i>												2	
	<i>Loxechinus albus</i>	73	10	1	1	8	5	1	5				2	5
	<i>Pyura chilensis</i>												2	

1051 Continuation: Table 3.

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Group	Scientific name	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total
Macroalgae	<i>Chondracanthus chamosoi</i>													11
	<i>Durvillaea incurvata</i>	13	154	569	970	1989	2235	1259	871	834	792	954	1358	13953
	<i>Macrocystis pyrifera</i>	60	120	87	150	228		1		2	8	5	2	663
	<i>Lessonia spicata</i>	90	428		89	727	95		531	852	1239	229	136	4416
	<i>Lessonia trabeculata</i>					8	3				611	476	1	1099
	<i>Pyropia sp.</i>		3	1	4	2	4	7	2	41	73	36	10	184
	<i>Mazzaella laminarioides</i>	14	101	24	3			1	3	1		12	6	188
	<i>Sarcothalia crispata</i>	265	195	904	268	208	649	320	117	81	113	960	173	4774
	<i>Sarcopeltis skottsbergii</i>	7	38	12			1	320	6		1	6		419
Fish	<i>Dissostichus eleginoides</i>	5												5
	<i>Genypterus chilensis</i>	10											15	32
	<i>Genypterus blacodes</i>													10
	<i>Genypterus maculatus</i>													19
	<i>Cilus gilberti</i>					6	1						2	43
	<i>Merluccius gayi gayi</i>	2												2
	<i>Merluccius australis</i>					4			4		20	13	1	152
	<i>Callorhynchus callorhynchus</i>											5	2	20
	<i>Odontesthes regia</i>	26	20			236								282
	<i>Psammobatis sp.</i>													239
	<i>Zearaja chilensis</i>	36			28		8	28	81	100	194	115	32	732
	<i>Brama australis</i>					4			4		20	13	1	152
	<i>Sprattus fuegensis</i>				2									4
	<i>Thyrsites atun</i>	119	38	13	109	237	19	6	4	5	8	2	5	725
Mollusks	<i>Venus antiqua</i>													1
	<i>Aulacomya atra</i>					2								7
	<i>Mytilus chilensis</i>					1								15
	<i>Fissurella sp.</i>													100
	<i>Fissurella nigra</i>	1	2	5	4					3				16
	<i>Concholepas concholepas</i>	6	42	34	41	48	36	11	4	6	4		3	647
	<i>Dosidicus gigas</i>						1					147	242	390
Crustaceans	<i>Lithodes santolla</i>													9
	<i>Metacarcinus edwardsi</i>													2
Other	<i>Loxechinus albus</i>	10	23	4	48	7	67	18	85	94	143	53	31	694
	<i>Pyura chilensis</i>				7			5		1	1	2	1	19

Table 4.- Four-phase extraction trajectory (2000–2024) for *Durvillaea incurvata* and *Lessonia spicata*, showing annual extraction ranges and associated governance milestones for LML-MUMPA. Phases reflect transitions in harvesting pressure, institutional capacity and management-plan implementation: Phase I, pre-designation (2000–2008); Phase II, rapid escalation during the implementation gap (2009–2015); Phase III, peak extraction (2016–2019); Phase IV, post-regulation with fluctuating intensity (2020–2024). Peak landings coincided with the absence of an operational management plan.

Phase	Period	<i>D. incurvata</i> (tons/year)	<i>L. spicata</i> (tons/year)	Governance milestone
I: Pre-intensification	2000-2008	0–22	0	AMCP-MU created (2005), no Management Plan
II: Rapid escalation	2009-2015	144–884	90–428	MEABRs active, unmonitored extraction
III: Peak extraction	2016-2019	792–2,235	531–1,239	Management Plan approved (2019), first harvest bans
IV: Post-regulation	2020-2024	792–1,358	136–1,239	Enforcement increasing, monitoring pilot (this study)

Table 5.- Ecological indicator species proposed for the LML-MUMPA monitoring framework, integrating scientific literature (SL) and local ecological knowledge (LEK) contributed by artisanal fishers during participatory workshops (March 2015, n = 35 stakeholders). SL+LEK indicates species validated by both sources. Species mentioned by at least 60% of workshop participants were retained as LEK indicators. Distribution ranges based on FishBase (Froese and Pauly, 2026) and regional literature.

Habitat	Zone	Group	Scientific name	Distribution	Knowledge source
Rocky	Intertidal	Invertebrate	<i>Fissurella picta</i>	35.0°S – 55.0°S	SL
			<i>Nucella crassilabrum</i>	27.0°S – 42.0°S	SL
			<i>Scurria ceciliana</i>	18.0°S – 53.0°S	SL
			<i>Scurria scurra</i>	18.0°S – 55.0°S	SL
			<i>Scurria zebrina</i>	18.0°S – 55.0°S	SL
			<i>Toncia chilensis</i>	8.0°S – 56.0°S	SL
			<i>Toncia elegans</i>	8.0°S – 40.0°S	SL
			<i>Crepidatella dilatata</i>	34.0°S – 55.0°S	SL
			<i>Macruronus magellanicus</i>	40.0°S – 56.0°S	SL
			<i>Bathyraxa brachiurops</i>	38.0°S – 54.0°S	SL
		Fish	<i>Austromenidia nigricans</i>	38.0°S – 56.0°S	SL
			<i>Dissostichus eleginoides</i>	38.0°S – 56.0°S	SL
			<i>Hippoglossina mystacium</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen breviceauda</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen canina</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen cornucola</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen longipes</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen sima</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen tessellata</i>	38.0°S – 56.0°S	SL
			<i>Patagonotothen wiltoni</i>	38.0°S – 56.0°S	SL
			<i>Merluccius australis</i>	36.0°S – 56.0°S	SL
			<i>Paralichthys patagonicus</i>	38.0°S – 56.0°S	SL+LEK
			<i>Calliclinus nudiventris</i>	38.0°S – 55.0°S	LEK
			<i>Calliclinus geniguttatus</i>	30.0°S – 55.0°S	LEK
			<i>Sebastes capensis</i>	18.0°S – 55.0°S	LEK
			<i>Cheilodactylus variegatus</i>	5.0°S – 42.0°S	LEK
			<i>Congiopodus peruvianus</i>	5.0°S – 56.0°S	LEK
			<i>Isacia conceptionis</i>	5.0°S – 55.0°S	LEK
			<i>Pinguipes chilensis</i>	3.0°S – 54.0°S	LEK
Sandy	Intertidal	Invertebrate	<i>Gliceridae</i>	19.3°S – 55.1°S	SL
			<i>Excirrolana hirsuticauda</i>	27.0°S – 43.0°S	SL

Table 6.- Annual monitoring calendar for priority indicator species within LML-MUMPA. Shaded cells denote months during which field surveys are recommended based on species detectability, seasonal behavior and habitat accessibility. Monitoring concentrates in two seasonal campaigns: summer (January–March) and spring (October–November). The calendar was co-designed with artisanal fishers to align with seasonal weather patterns and fishing activities, ensuring operational feasibility and community participation throughout the annual monitoring cycle.

Species	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
Fish												
<i>Pinguipes chilensis</i>												
<i>Congiopodus peruvianus</i>												
<i>Paralichthys patagonicus</i>												
<i>Cheilodactylus variegatus</i>												
<i>Sebastes capensis</i>												
<i>Iscacia conceptionis</i>												
Macroalgae												
<i>Lessonia trabeculata</i>												
<i>Durvillaea incurvata</i>												

Table 7.- Sensitivity matrix for ecological indicators used in the LML-MUMPA monitoring program, integrating ecological sensitivity, detectability by artisanal fishers, sampling cost and management relevance. Indicators were ranked through participatory multi-criteria analysis during DPSIR workshops with 35 stakeholders (March 2015). Priority rank 1 = highest. Cost categories: Low (< USD 10 per sample), Medium (USD 10–50 per sample), High (> USD 50 per sample). Rankings reflect both scientific criteria and community-validated operational feasibility.

Indicator	Ecological Sensitivity	Fisher Detectability	Cost per Sample	Management Relevance	Priority Rank
<i>D. incurvata</i> cover	High	High	Low (visual survey)	High	1
<i>L. spicata</i> disc size	Medium	High	Low (caliper)	High	2
Epifauna richness	High	Low	Medium (sorting + ID)	Medium	3
Fish presence	Medium	High	Medium (census)	Medium	4
Substrate stability	Low	High	Low (visual)	Low	5

1108 Table 8.- Estimated annual cost (USD) of implementing the LML-MUMPA pilot monitoring program. Costs include underwater
 1109 surveys, macroalgae population assessments, macroinvertebrate identification, environmental data collection and landing-record
 1110 monitoring. Shaded cells indicate months of concentrated field activity. Cost estimates are based on 2024 prices and include personnel,
 1111 equipment, laboratory processing and data management. Community-led implementation reduces costs by approximately 30% relative
 1112 to institution-led scenarios, with annual budgets of USD 70,000 and USD 100,000 respectively.

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Annual cost of the monitoring plan for indicator species in LML-MUMPA													
Activities/Month	January	February	March	April	May	June	July	August	September	October	November	December	Cost (USD)
Fish													
Visual censuses.													40,000
Underwater filming.													
Analysis of photographic records.													
Assessment of fish communities present in the SSUs using similarity indices.													
Macroalgae													
Population characterization of brown algae meadows within the LML-MUMPA (size structure, biomass density). Biodiversity characterization of macroinvertebrates within the fixation discs in brown algae meadows of the LML-MUMPA. Biodiversity characterization of macroinvertebrates among the fixation discs in brown algae meadows of the LML-MUMPA. Biodiversity characterization of fish associated with the canopy in brown algae meadows of the LML-MUMPA. Determination of environmental variables associated with the biodiversity of macroinvertebrates and fish in brown algae meadows. Temporal validation of the list of indicator species for the ecosystem's health status. Collection of information regarding volumes of brown algae collection and/or landing in the study area. Collection of information regarding variations in fishing effort on brown algae meadows in the study area.												60,000	
Total implementation cost (USD)													100,000

Note: Cost estimates reflect 2024 prices in southern Chile. The community-led scenario (USD 70,000/year) assumes fisher collaboration with shared equipment and stipends equivalent to average fishing income across 20 sampling days in two seasonal campaigns. The institution-led scenario (USD 100,000/year) includes vessel leasing, specialized personnel at 25% FTE and technical support. Both scenarios cover laboratory processing, taxonomic identification, data management and reporting. Major capital investments are assumed available through existing institutional partnerships.

Legend figures

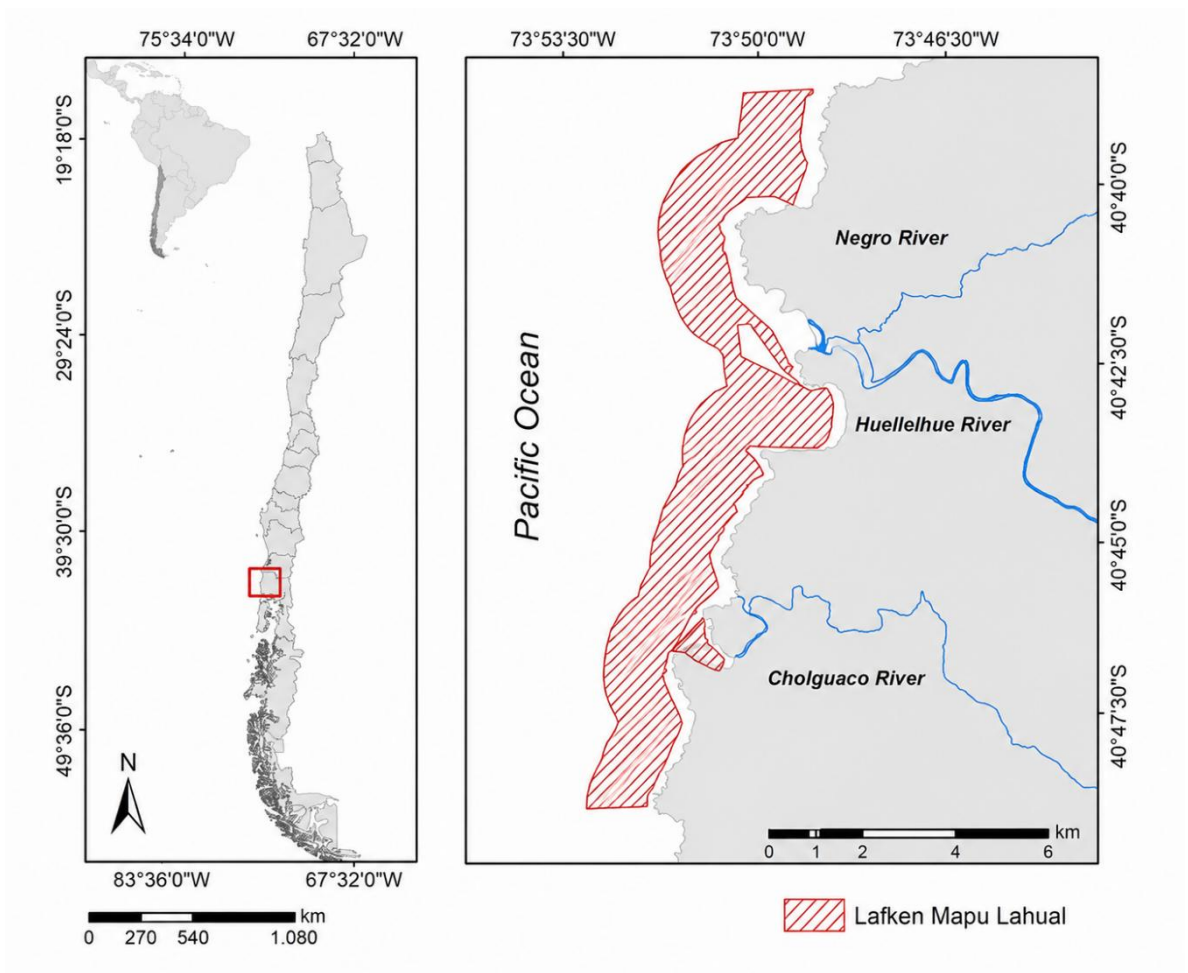


Figure 1.- Geographic location of the Lafken Mapu Lahual Multiple-Use Marine and Coastal Protected Area (LML-MUMPA) in southern Chile. The protected area covers 4,463 ha, including a 1 nautical mile marine component. Main rivers (Huellelhue and Cholguaco) and adjacent coastal communities are shown. LML-MUMPA is the only protected area of its category within the Araucana Marine Ecoregion and supports artisanal fisheries and Mapuche-Huilliche traditional marine use. Map projection: WGS84; GPS accuracy ± 5 m.

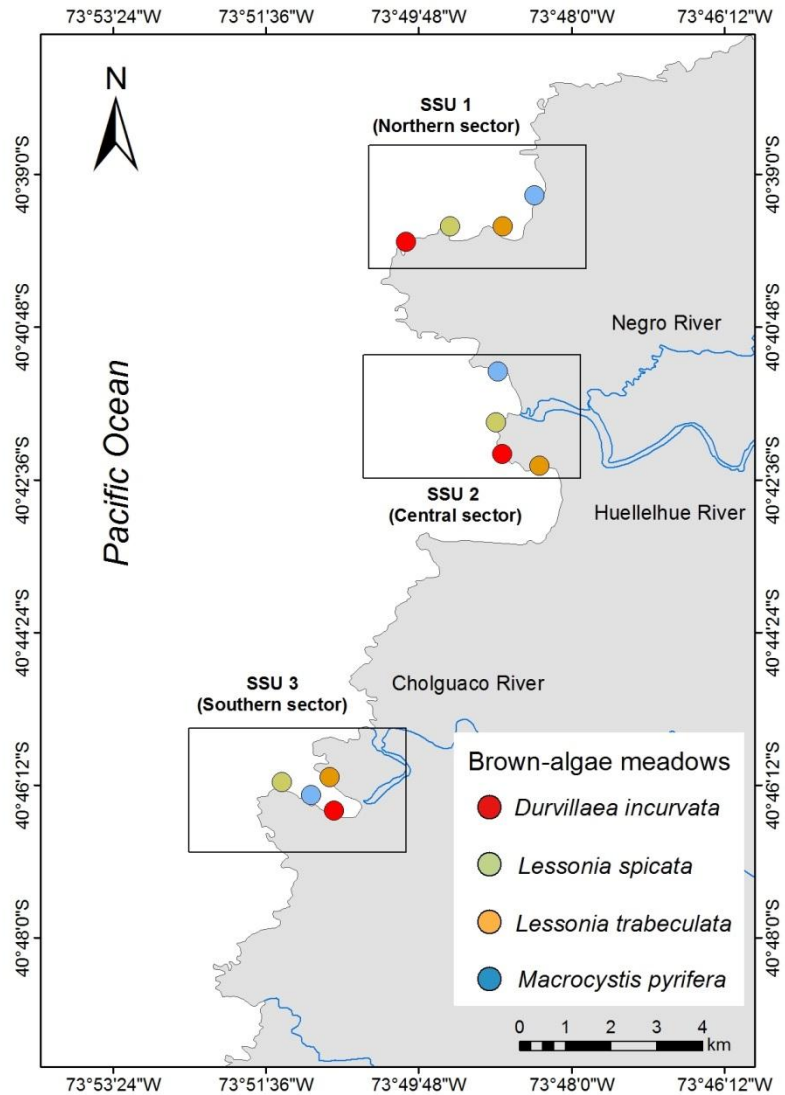


Figure 2.- Spatial distribution of three Spatial Sampling Units (SSUs) within LML-MUMPA, showing sampling locations for brown-algae meadow surveys during 2014–2015. Colored circles indicate presence of four macroalgae species: *Durvillaea incurvata* (red), *Lessonia spicata* (olive green), *Lessonia trabeculata* (orange) and *Macrocystis pyrifera* (blue). SSU 1 represents the highest wave exposure and extraction pressure, decreasing southward toward SSU 3, defining the social-ecological gradient structuring this study.

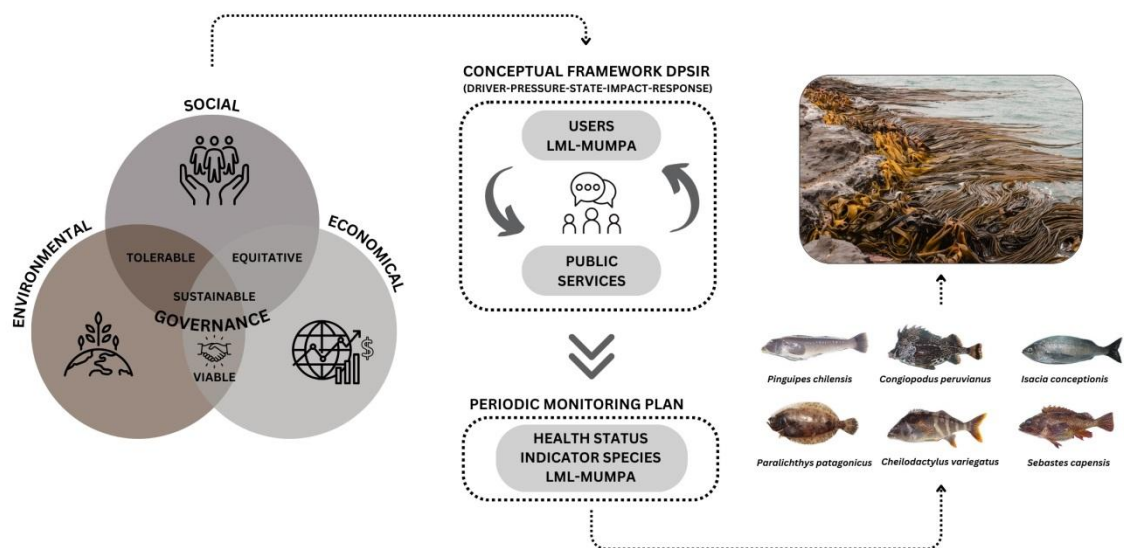


Figure 3.- Conceptual DPSIR framework applied in LML-MUMPA to link human drivers of brown-algae extraction with ecosystem state changes, impacts and governance responses. The diagram summarizes the participatory co-design process involving 35 stakeholders including artisanal fishers, Mapuche-Huilliche Indigenous representatives, government agencies and NGOs. Arrows indicate causal relationships between system components. The framework served as the organizational structure through which scientific data and local ecological knowledge were jointly translated into operational indicators and management thresholds.

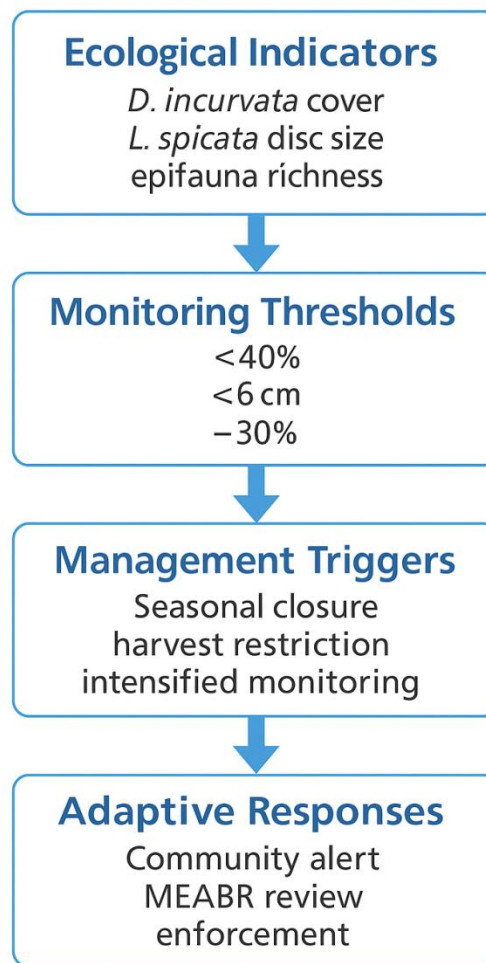


Figure 4.- Adaptive management logic model for the LML-MUMPA participatory monitoring framework. Ecological indicators including *D. incurvata* canopy cover, *L. spicata* holdfast diameter and fixation-disc epifaunal richness are evaluated against quantitative thresholds (40%, 6 cm and 30% decline respectively) to trigger sequential management responses ranging from harvest restrictions to temporary closure and intensified monitoring. The model operationalizes the feedback loop between ecological assessment, stakeholder deliberation and governance action within the social-ecological system.

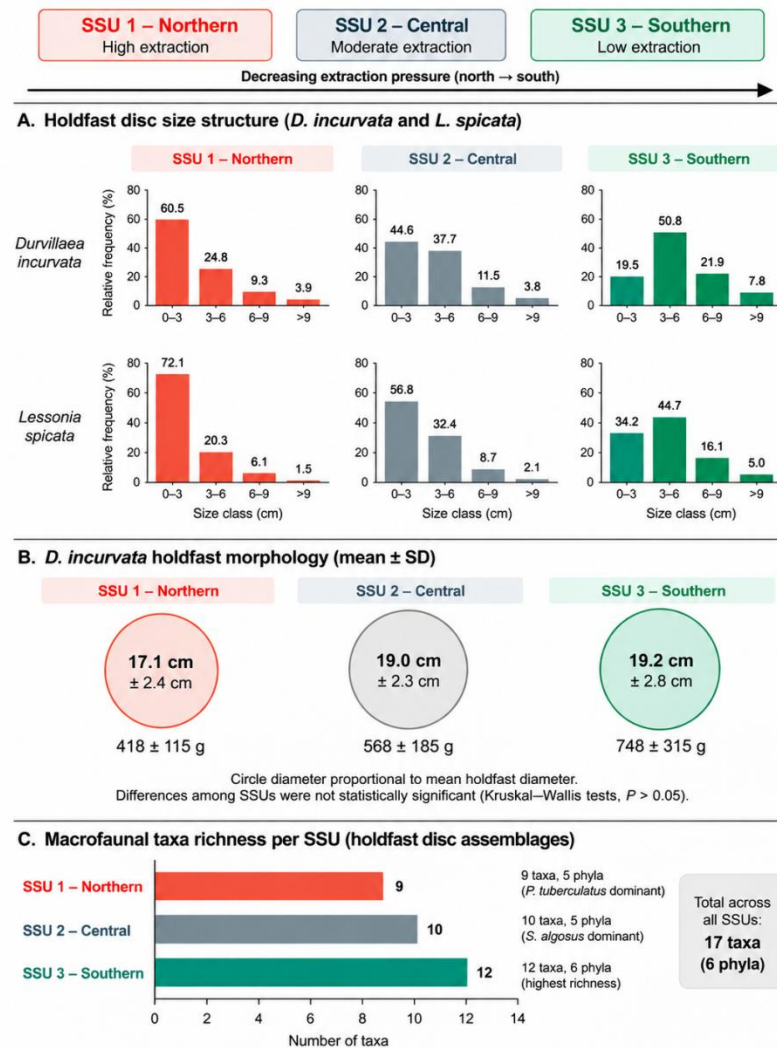


Figure 5.- Spatial ecological patterns across the three Spatial Sampling Units (SSUs) in LML-MUMPA. (A) Relative frequency of holdfast size classes for *Durvillaea incurvata* and *Lessonia spicata*, showing differences in population structure among SSUs. (B) Mean diameter and wet weight of *D. incurvata* holdfasts, with circle size proportional to mean diameter; differences among SSUs were not significant (Kruskal–Wallis, $P > 0.05$). (C) Cumulative macrofaunal taxonomic richness associated with *D. incurvata* holdfasts in each SSU (Table 2). Overall, the panels show contrasting spatial patterns in kelp structure and associated biodiversity.



Figure 6.- Representative photographs of intertidal *Lessonia spicata* and *Durvillaea incurvata* meadows at contrasting wave-exposure levels across the three Spatial Sampling Units of LML-MUMPA. Images illustrate differences in canopy density and structural complexity associated with varying degrees of hydrodynamic stress and extraction pressure, reflecting the social-ecological gradient documented across the protected area.

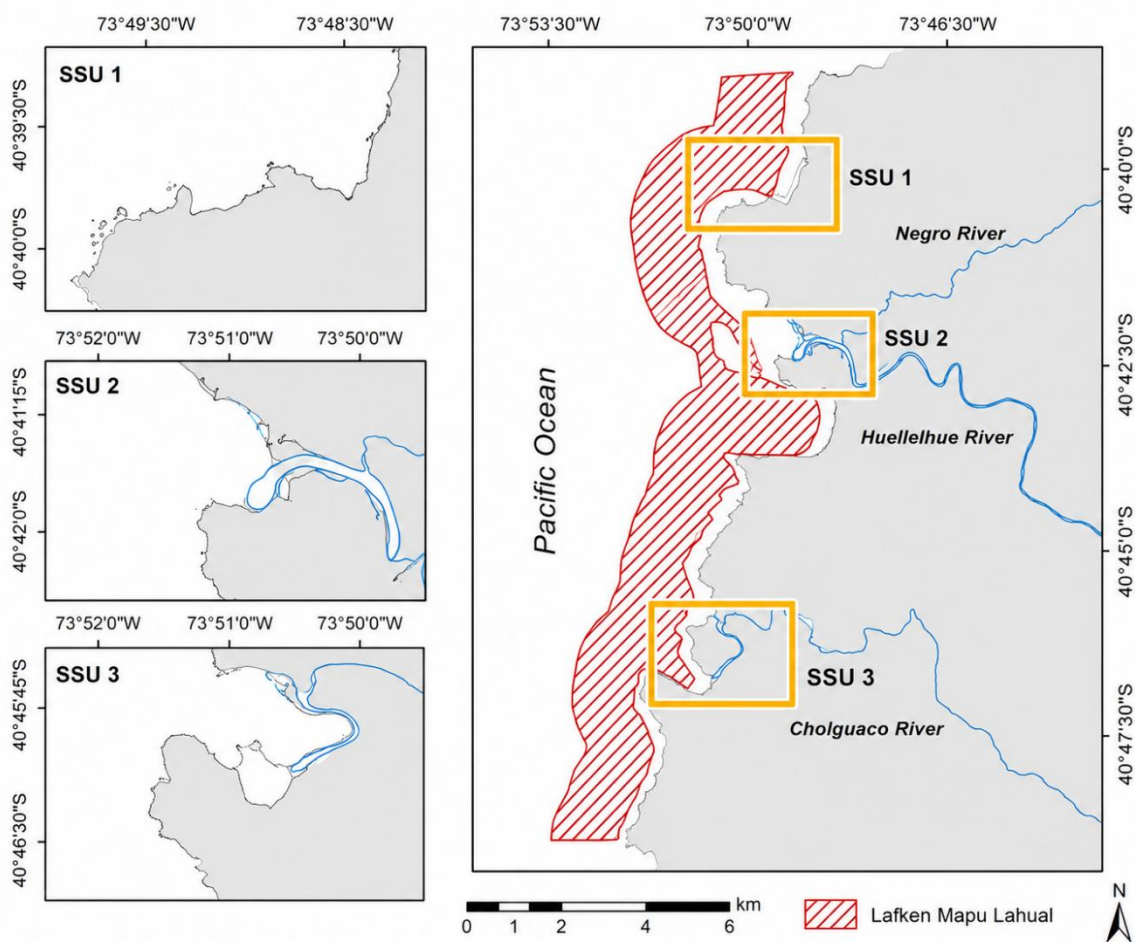


Figure 7.- Satellite imagery of the three Spatial Sampling Units (SSUs) within LML-MUMPA (yellow rectangles, right panel) with detailed views of each sector (left panels): SSU 1, northern sector (Palería); SSU 2, central sector (Huellehue); SSU 3, southern sector (Cónдор Cove). The hatched area delineates the LML-MUMPA boundary. Base imagery from Google Earth. Map projection: WGS84.

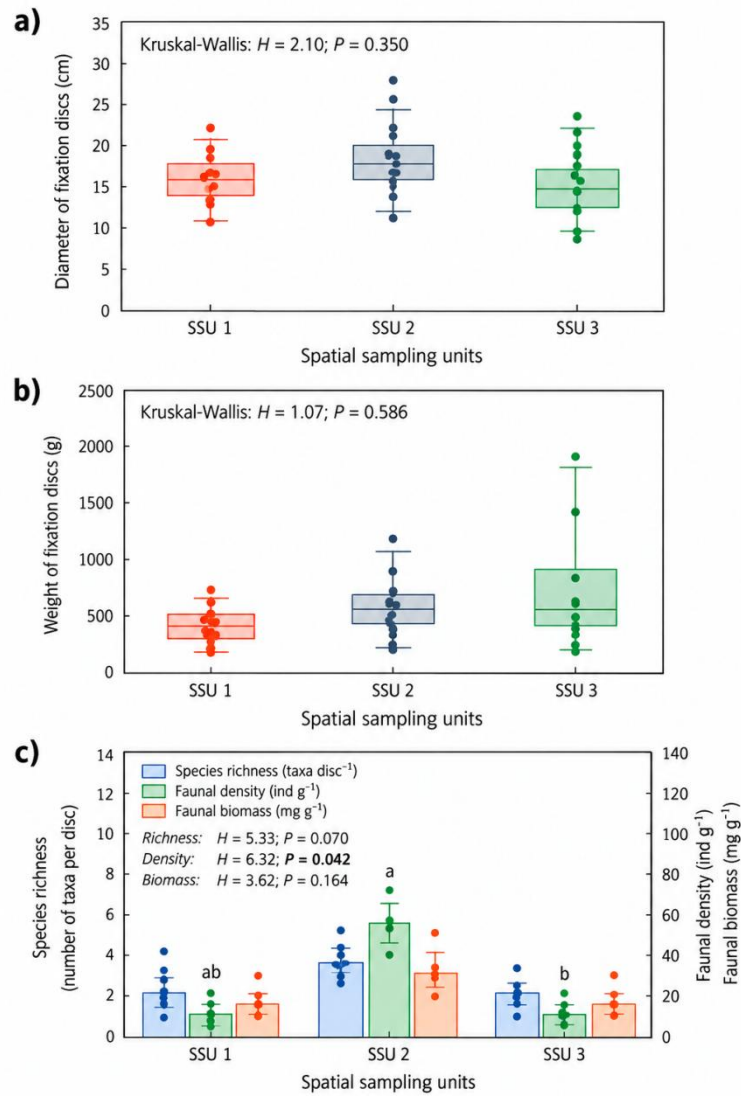
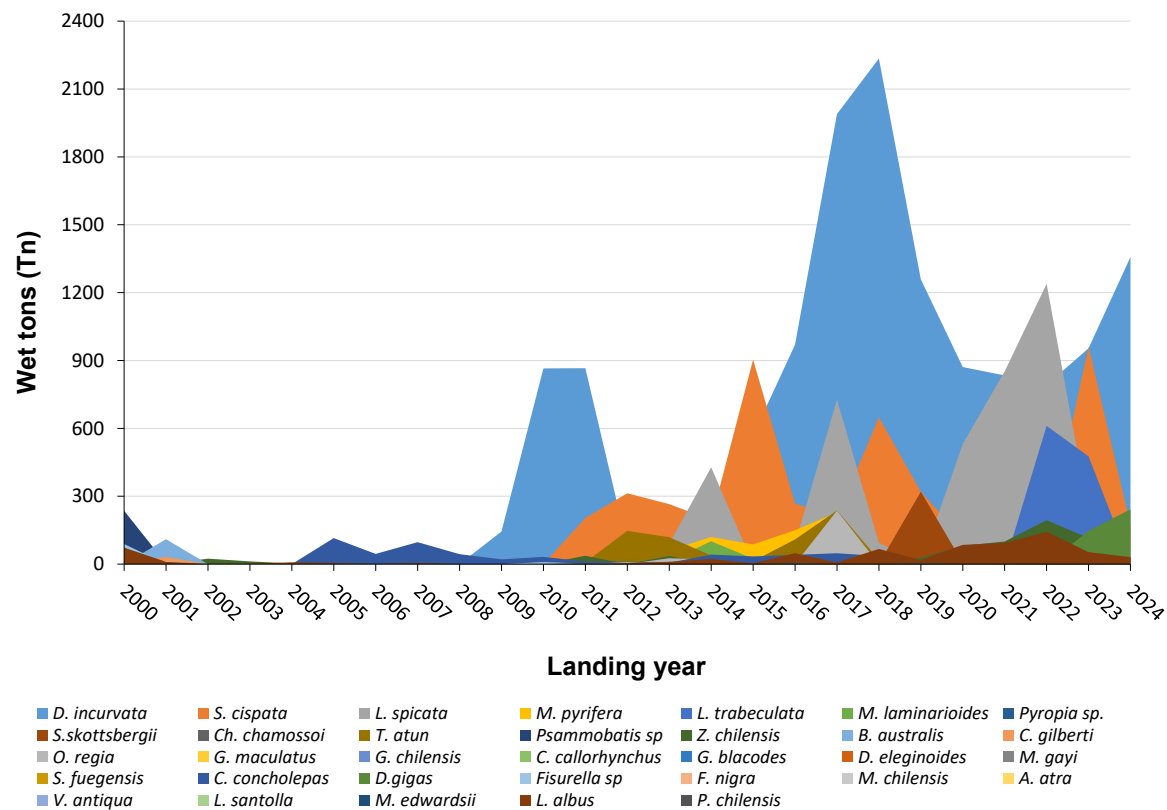


Figure 8.- Spatial variation in *Durvillaea incurvata* holdfast morphology and associated macrofauna across the three Spatial Sampling Units (SSUs) of LML-MUMPA. (a) Holdfast diameter, (b) holdfast weight, and (c) associated species richness, faunal density, and biomass. Individual observations are shown with boxplots in (a–b) (SSU 1: $n = 5$; SSU 2: $n = 10$; SSU 3: $n = 5$), whereas bars in (c) represent mean $\pm$ SE based on five holdfasts per SSU. Statistical results are reported within each panel. Different lowercase letters in (c) indicate significant pairwise differences in faunal density among SSUs (Dunn's post-hoc test with Holm adjustment, $P < 0.05$).

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1407 Figure 9.- Annual landings (wet tons) recorded at Bahía Mansa during 2000–2024,
1408 reflecting regional extraction trends from within and adjacent to LML-MUMPA. Stacked
1409 bars represent macroalgae (*Durvillaea incurvata*, *Lessonia spicata*, *Sarcothalia crispata*),
1410 fish and invertebrates (*Loxechinus albus*, *Concholepas concholepas*). Four extraction
1411 phases are identifiable: early exploration (2000–2008), expansion (2009–2015), peak
1412 exploitation (2016–2019) and regulatory adjustment (2020–2024). Source: SERNAPESCA
1413 (accessed November 2024).