# Policy Pathways for Enabling Mussel Shell Reuse in Marine Restoration in Chile

María José Martinez-Harms[1,2,3,4*], Uranía Lavín[2,3], Daniela Sotomayor-Gerding[5], Begoña Peceño[4,5], Nelson A. Lagos[2,4]

[1]Facultad de Ingeniería y Ciencias - Universidad Adolfo Ibáñez, Santiago de Chile

[2]Centro de Investigación e Innovación para el Cambio Climático, Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile

[3]Institute of Ecology and Biodiversity (IEB), Concepción, Chile

[4]Millennium Institute in Coastal Socio-Ecology, Pontificia Universidad Católica de Chile, Santiago, Chile

[5]Escuela de Prevención de Riesgos y Medioambiente, Facultad de Ciencias del Mar, Universidad Católica del Norte, Coquimbo, Chile

*Corresponding author: mmartinez-harms@ieb-chile.cl

## Abstract

Chile is the world's second-largest producer of mussels and the leading exporter, harvesting approximately 400,000 t/year, of which about 30% becomes shell waste. While this biomaterial poses a growing disposal challenge, it also represents an opportunity for marine ecological restoration. In southern Chile, where mussel farming is concentrated, efforts to reuse shells as nature-based solutions (NbS) face legal and institutional constraints.

This study examines the regulatory conditions shaping shell reuse through analysis of national, regional, and local legal and policy instruments, complemented by a participatory workshop

with 50 stakeholders. Instruments were assessed across six policy domains and coded by legal function (enabling, restrictive, or ambiguous) and regulatory effects, identifying hard barriers, contextual friction, and underutilized enabling levers.

Results show that although current regulations—particularly the classification of shells as waste—formally restrict marine reuse, key constraints extend beyond explicit prohibitions. Interpretive ambiguity, procedural uncertainty, and fragmented institutional mandates play a central role in limiting restoration initiatives. Workshop insights suggest that overcoming these barriers does not require comprehensive legal reform, but can be achieved through reinterpretation of existing rules, technical standard-setting, and improved inter-agency coordination, supported by pilot projects with strong legitimacy.

These findings highlight that shell reuse is not only a legal and technical challenge, but also a cultural and ethical one, requiring approaches that integrate ecological goals with social legitimacy and community participation. The Chilean case illustrates how regulatory innovation can emerge within existing legal systems, offering transferable insights for advancing circular NbS in coastal governance contexts.

**Keywords:** marine restoration, mytiliculture, aquaculture, environmental policy, governance, circular economy, shell waste.

## 1. Introduction

Coastal and marine ecosystems face increasing pressures from climate change, pollution, habitat degradation, and unsustainable resource extraction [1]. In response, there is growing global interest in integrated ocean governance approaches that promote ecosystem resilience and sustainability [2,3]. Among these, nature-based solutions (NbS) are gaining traction as policy tools that harness ecological processes to deliver benefits for biodiversity, climate

45 adaptation, and human well-being [4,5]. However, the implementation of NbS in marine and
46 coastal contexts frequently confronts legal and institutional barriers, particularly when they
47 rely on innovative uses of materials traditionally classified as waste [6,7].

48 One such opportunity lies in the circular reuse of shell waste from aquaculture and seafood
49 industries. Globally, bivalve mollusks are produced in vast quantities, and their shells, often
50 discarded in landfills, can pose local environmental risks while also representing untapped
51 ecological value [8,9]. Their potential in restoration applications, such as reef construction [10],
52 sediment stabilization [11], and habitat provision, has been increasingly recognized, aligning
53 with circular economy principles and ecosystem-based management [12,13].

54 In Chile, the expansion of mussel aquaculture, concentrated in the Los Lagos Region (Northern
55 Patagonia; Figure 1), has led to the generation of shell waste, representing a significant fraction
56 of total production [14]. These materials are currently classified as industrial non-hazardous
57 waste under the national sanitary framework [15]. While a large portion has been revalorized
58 to produce agricultural lime [16], in practice, shell residues exceeding acceptable thresholds of
59 organic matter content—commonly around 2%—cannot be valorized through this process and
60 must instead be disposed of in landfills [14,15]. Consequently, the sector still faces economic
61 and environmental challenges associated with the large volumes generated, the costs of waste
62 management, and the reliance on predominantly land-based disposal and valorization pathways
63 [17].

64

65 At the same time, many coastal and benthic habitats in the region suffer from degradation due
66 to eutrophication, sedimentation, and historical overexploitation [18,19]. Paradoxically, while
67 shell waste represents a pressing disposal issue, it also holds ecological value as a biogenic
68 substrate for habitat restoration [11]. This approach is grounded in ecological principles,

specifically the positive feedback on biodiversity arising from the accumulation of shelled organisms and biogenic build-up [20]. Restoring mussel reefs rebuilds habitat structure and function and also may reactivate carbonate buffering and dissolution processes, enhancing local chemical resilience and long-term ecosystem stability [21]. Through shell dissolution, $CO_3^{2-}$ ions are released, increasing alkalinity and mitigating acidification in coastal waters [22]. This process underlies the taphonomic feedback hypothesis, whereby shell accumulation promotes further calcifier settlement and carbonate cycling, sustaining shellfish reefs over time [20]. This duality, waste burden vs. restoration opportunity, sits at the core of regulatory and institutional tensions that this study seeks to unpack.

Some countries have begun to address these barriers through clearer regulatory frameworks. For example, Australia, the United States, and Japan have established regulatory frameworks that recognize the ecological value of mollusk shells and explicitly support their reuse in restoration, including oyster reef rebuilding, coastal protection, and habitat enhancement projects [23,24]. These cases demonstrate that targeted legal adaptations can enable circular approaches to marine restoration while maintaining environmental safeguards. In many regulatory systems, however, the reuse of marine organic waste is hindered by outdated or fragmented legal frameworks [25]. Classification ambiguities, permitting hurdles, and institutional overlap contribute to governance bottlenecks that impede the operationalization of circular NbS [26,27].

Chile is one of the world's leading mussel aquaculture producers and a country with strong policy commitments to biodiversity, climate adaptation, and sustainable coastal development [28,29]. The mussel aquaculture industry is located mostly in north-patagonian waters (e.g, Los Lagos Region), where the production and accumulation of shell waste coexists with opportunities for restoration of degraded marine ecosystems [30]. Yet, pilot projects aiming to

reuse shells in NbS, in the Los Lagos Region, have encountered significant normative and procedural obstacles. These include the lack of clear legal definitions, regulatory pathways, and coordination mechanisms across environmental, productive, and territorial institutions.

This study examines Chile's legal and institutional framework governing mussel aquaculture, waste management, environmental protection, and marine restoration through an applied governance and policy analysis. The analysis draws on a structured review of 33 national legal instruments (laws, decrees, and resolutions) and 7 national and regional instruments, including strategies, plans, and policy frameworks relevant to biodiversity, climate change, and circular economy objectives. 26 ordinances (13) and communal regulatory plans (13) from the Los Lagos Region are reviewed as part of the broader governance context, reflecting how national regulations are interpreted, operationalized, and constrained at the local level.

Although international experiences—particularly from Australia, the United States, and Japan—demonstrate viable regulatory pathways for shell-based coastal restoration, the governance and regulatory conditions shaping the feasibility of such nature-based solutions have not been systematically examined in the Chilean context. This study addresses this gap through an applied governance analysis that examines how legacy legal frameworks can either constrain or be strategically reinterpreted to enable policy innovation within existing institutional arrangements.

Specifically, this study asks: (1) how Chile's current legal and institutional framework constrains or enables the reuse of mussel shell waste in marine ecological restoration; and (2) which regulatory levers embedded in existing policy architectures could be strategically reinterpreted and coordinated to operationalize circular nature-based solutions without requiring major legislative reform.

We make three contributions to marine policy scholarship: first, it demonstrates how legacy waste regulations structurally constrain circular NbS in marine contexts; second, it introduces a functional legal-mapping approach to distinguish hard barriers, friction, and enabling levers; and third, it shows how regulatory reinterpretation—rather than reform—can enable restoration innovation in formalized legal systems.

## 2. Methods

This study employed a qualitative methodology combining legal and policy document analysis with participatory engagement to identify regulatory barriers and opportunities for the reuse of mussel shell waste in coastal restoration projects in southern Chile.

### 2.1. Study area

This study focuses on the coastal zone of the Los Lagos Region in southern Chile (41.5°–43.5°S, 72.5°–74.5°W), with particular attention to Chiloé Island and the Reloncaví Sound (Figure 1). These areas represent the core of Chile's mussel (*Mytilus chilensis*) aquaculture industry, hosting the highest density of aquaculture concessions in the country [31] and generating substantial volumes of shell residues [14].

The Reloncaví Sound, in particular, plays a critical ecological and productive role. Due to its sheltered fjord-like conditions, relatively stable salinity, and lower exposure to ocean acidification, the area functions as a natural climate refugium for early life stages of mollusks [32]. It serves as a key "semillero" or mussel spat collection area where increased recruitment and survival, underpinning the sustainability of the entire industry [19,33]. These unique environmental attributes make the Reloncaví Sound not only a hub of aquaculture productivity but also a strategic location for the development of nature-based solutions (NbS) aimed at marine ecosystem restoration and resilience under changing climate conditions.

The combination of ecological sensitivity, productive value, and regulatory complexity in this area provides an ideal context for examining the governance, legal frameworks, and feasibility of using mussel shell residues as a substrate for benthic restoration aligned with circular economy principles.

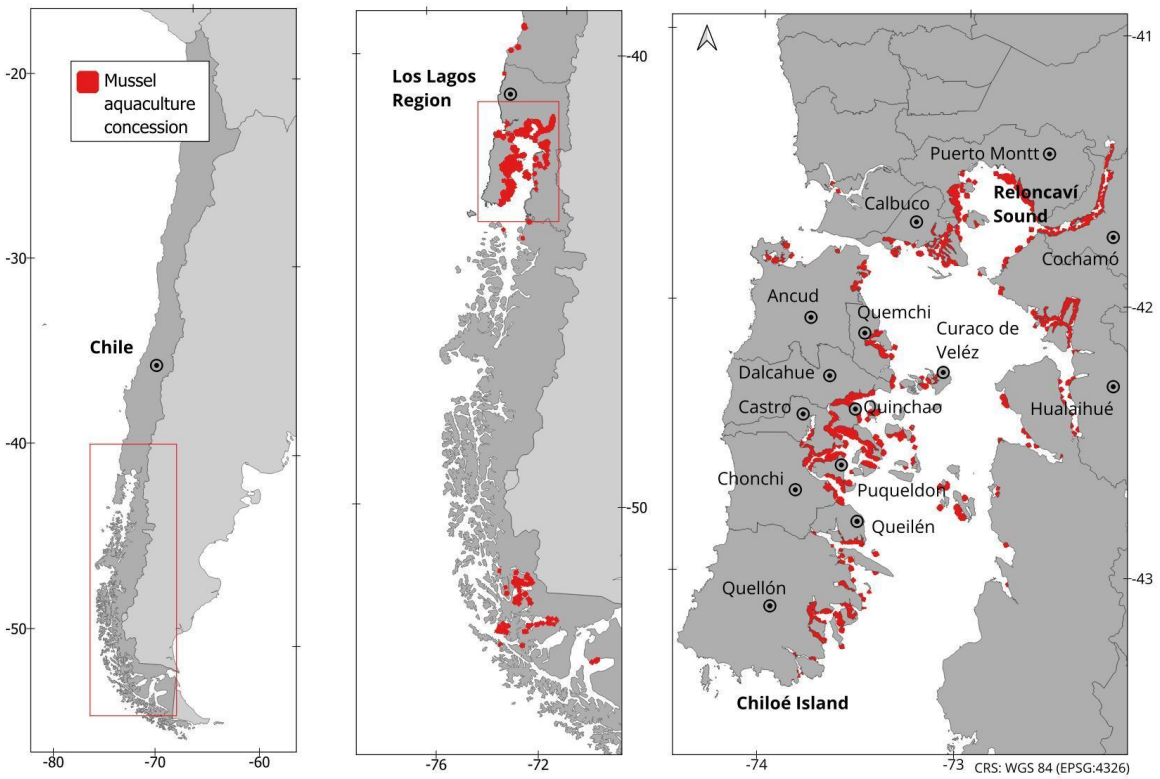


**Figure 1. Study area in southern Chile's Los Lagos Region.** The map highlights Chiloé Island and the Reloncaví Sound and fjord, the core zones of mussel aquaculture and significant production of shell waste), which are being considered for reuse in coastal and benthic restoration efforts under nature-based solutions (NbS).

## 2.2. Regulatory and institutional document analysis

We conducted a structured review of national and regional legal and policy instruments related to aquaculture, environmental protection, waste management, biodiversity conservation, and coastal governance. The reviewed instruments were organized into six core policy domains

(hereafter also referred as regulatory blocks) that capture the main institutional arenas shaping the feasibility of mussel shell reuse in coastal restoration:

A. **Ecological Restoration and Nature-based Solutions (NbS):** Policies and legal definitions governing ecological restoration, NbS eligibility, and planning instruments, assessing whether shell reuse can be recognized as a legitimate restoration activity.
B. **Waste Management and Circular Economy:** Legal classification of mussel shells (e.g., waste, by-product, secondary raw material) and associated regulatory conditions under Extended Producer Responsibility (EPR) schemes, sanitary regulations, and valorization policies.
C. **Use of the coastal zone and Coastal Concessions:** Governance of coastal use rights, including aquaculture and restoration concessions, and the legal compatibility of NbS interventions within existing spatial regimes of the public maritime domain.
D. **Sanitary regulations and traceability:** Health and sanitary standards for the transport, handling, and reuse of shell residues, including biosecurity, disease control, traceability requirements, and regulation of potential risks associated with shell processing.
E. **Governance and Participation:** Inter-agency coordination, stakeholder engagement mechanisms, and institutional capacity for cross-sectoral implementation.
F. **Environmental Impact Assessment (EIA):** Conditions under which shell-based restoration projects trigger EIA processes, including classification challenges, procedural uncertainty, and ambiguous risk thresholds.

### 2.3. Participatory workshop

To complement the legal analysis and contextualize it in institutional practice, a participatory workshop titled “From Waste to Restoration: Legal Framework and Shell Management for Coastal Recovery” was held in Castro, Chiloé, in June 2025 [34]. The workshop gathered 50

stakeholders from public institutions (24,5%), aquaculture companies (35,8%), research institutions (28,3%), and local communities (11,3%). It aimed to co-produce regulatory insights and practical recommendations for enabling the reuse of mussel shells in ecological restoration. Prior to the workshop, all participants signed an informed consent form, and the study received ethical approval from the Ethics Committee of Universidad Santo Tomás.

Participants were organized into five thematic working groups aligned with the study's policy domains or blocks (A-E), with block F addressed as a cross-cutting axis. Each group worked with a structured matrix designed to capture four dimensions: Regulatory Gaps, Opportunities, Recommendations, and Observations. Participants were guided by a thematic question set to support the documentation and synthesis of results. The session followed a structured format: (1) plenary briefing, (2) group work, (3) synthesis, and (4) plenary presentation and validation. Facilitation protocols, timing mechanisms, and templates were used to ensure consistency across groups.

The resulting matrices, along with the plenary synthesis, provided a grounded diagnosis of normative barriers and institutional bottlenecks, as well as actionable and context-specific recommendations. These materials were subsequently systematized and integrated into the study's analysis to inform the proposed legal and policy pathways.

### 2.4. Analytical framework

To assess how Chile's regulatory landscape supports or constrains the reuse of mussel shell waste in marine ecological restoration, we applied a cross-sectoral policy mapping framework, combining legal and policy analysis with participatory validation. This framework was designed to examine how institutional arrangements shape the feasibility of circular resource use in practice, particularly for innovative or non-standard nature-based solutions.

The framework was applied to a multi-scalar dataset of regulatory and policy instruments relevant to aquaculture, waste management, biodiversity conservation, coastal governance, and environmental assessment. The core analysis focused on 33 national legal instruments (laws, decrees, and exempt resolutions issued between 1989 and 2024), complemented by 7 national and regional policy instruments (strategies, action plans, and governance agreements). To capture implementation-level dynamics, we also reviewed 26 subnational instruments from the Los Lagos Region, comprising municipal environmental ordinances (n = 13) and communal regulatory plans (PRCs; n = 13).

Subnational instruments were not treated as equivalent to national legislation in terms of legal hierarchy or binding force. Instead, they were included to characterize the implementation context in which national regulations are interpreted, operationalized, or constrained at the local level, and to identify sources of discretion, regulatory friction, and contextual ambiguity affecting pilot restoration initiatives. Instruments were therefore analyzed relationally, rather than weighted by formal legal authority, to capture interactions across governance levels.

Each instrument was systematically coded along multiple analytical dimensions, following a reproducible decision tree and explicit definitional criteria (Appendix A), applied exclusively to the Chilean regulatory dataset.

First, instruments were classified according to their legal function, defined as their formal orientation with respect to shell reuse in restoration:

- **Enabling**, when the instrument explicitly supports ecological restoration, valorization, or reuse of biogenic materials, or establishes mandates aligned with NbS;
- **Restrictive**, when the instrument prohibits or constrains marine reuse, particularly by framing shells as waste, pollutants, or sanitary risk;

- **Ambiguous**, when regulatory language is silent, discretionary, or internally inconsistent, resulting in implementation uncertainty.

Second, to capture how instruments operate in practice, each was coded according to its practical regulatory effect on shell reuse initiatives:

- **Regulatory gaps**, where key issues (e.g., classification, permitting, traceability) remain unregulated;
- **Friction points**, where overlapping mandates, contradictory rules, or procedural complexity impede implementation;
- **Grey zones**, where ambiguity leads to discretionary or variable enforcement.

Building on these dimensions, instruments were further synthesized into barrier types—hard regulatory barriers, contextual friction, contextual background influences, and core enabling levers—to support interpretative analysis and visualization. Instruments were also coded by governance level (national, regional, communal/local) and by policy domain, corresponding to the six analytical domains defined above.

The resulting coded dataset (Appendix B) enabled comparative analysis across policy domains, governance levels, and time periods. Aggregated outputs were used to generate visual syntheses highlighting concentrations of ambiguity, persistent regulatory bottlenecks, and clusters of enabling potential, emphasizing patterns of interaction rather than formal legal hierarchy. Stakeholder insights from the participatory workshop in Castro (Los Lagos Region) were used to validate coding decisions—particularly for grey zones and friction points—and to ground the analysis in implementation realities.

## 3. Results

### 3.1 Evolution of the Regulatory Framework

Chile's legal framework governing aquaculture, environmental protection, and waste management has evolved substantially between 1989 and 2024 (Figure 2). The regulatory dataset analyzed in this study comprises 33 binding legal instruments, including 14 laws, 12 decrees, and 7 exempt resolutions, which together define the formal legal architecture shaping the feasibility of mussel shell reuse in marine restoration.

Across this period, regulatory development has been uneven across policy domains (Figure 2). Ecological Restoration and Nature-based Solutions (Block A) and Governance and Participation (Block E) are comparatively recent domains, becoming more visible after 2010 and intensifying in the 2020s. These instruments reflect a gradual institutional shift toward restoration, climate adaptation, and participatory governance, although they remain weakly connected to operational rules governing aquaculture residues and marine materials. In contrast, Coastal use and concession regimes (Block C) constitute the most consistently regulated domain, reflecting the long-standing centrality of spatial control and access rights in Chile's marine governance. Instruments in this block span the entire temporal range of the analysis, anchoring aquaculture and coastal activities within the public maritime domain and establishing persistent constraints on novel marine uses.

Waste management and circular economy regulations (Block B) emerge primarily after 2000, growing concern over environmental protection, sanitary risk, and extended producer responsibility. This block concentrates a substantial share of regulations that frame aquaculture residues—including mussel shells—as waste, reinforcing disposal-oriented approaches and generating structural constraints for reuse in marine environments. The norms reinforced the classification of such waste, creating institutional and operational barriers to their reuse or valorization in marine ecosystems.

Environmental Impact Assessment (EIA; Block F) is represented by a smaller number of instruments, yet plays a disproportionate role in shaping implementation outcomes. Ambiguous thresholds and discretionary screening criteria place shell-based restoration initiatives in regulatory grey zones, increasing uncertainty and variability in project authorization.

Key milestones in the evolution of the framework include the General Fisheries and Aquaculture Law (1989) and the General Environmental Framework Law (1994), which established the foundations of Chile's fisheries and environmental governance. The early 2000s were marked by a consolidation of sanitary and waste-related regulations affecting mollusk production, while the period since 2022 has seen the adoption of restoration- and climate-oriented legislation, including the Climate Change Framework Law (Law 21.455) and the creation of the Biodiversity and Protected Areas Service (SBAP; Law 21.600). Overall, the temporal distribution of regulations reveals a layered regulatory system in which newer sustainability-oriented instruments coexist with older waste and sanitary regimes.

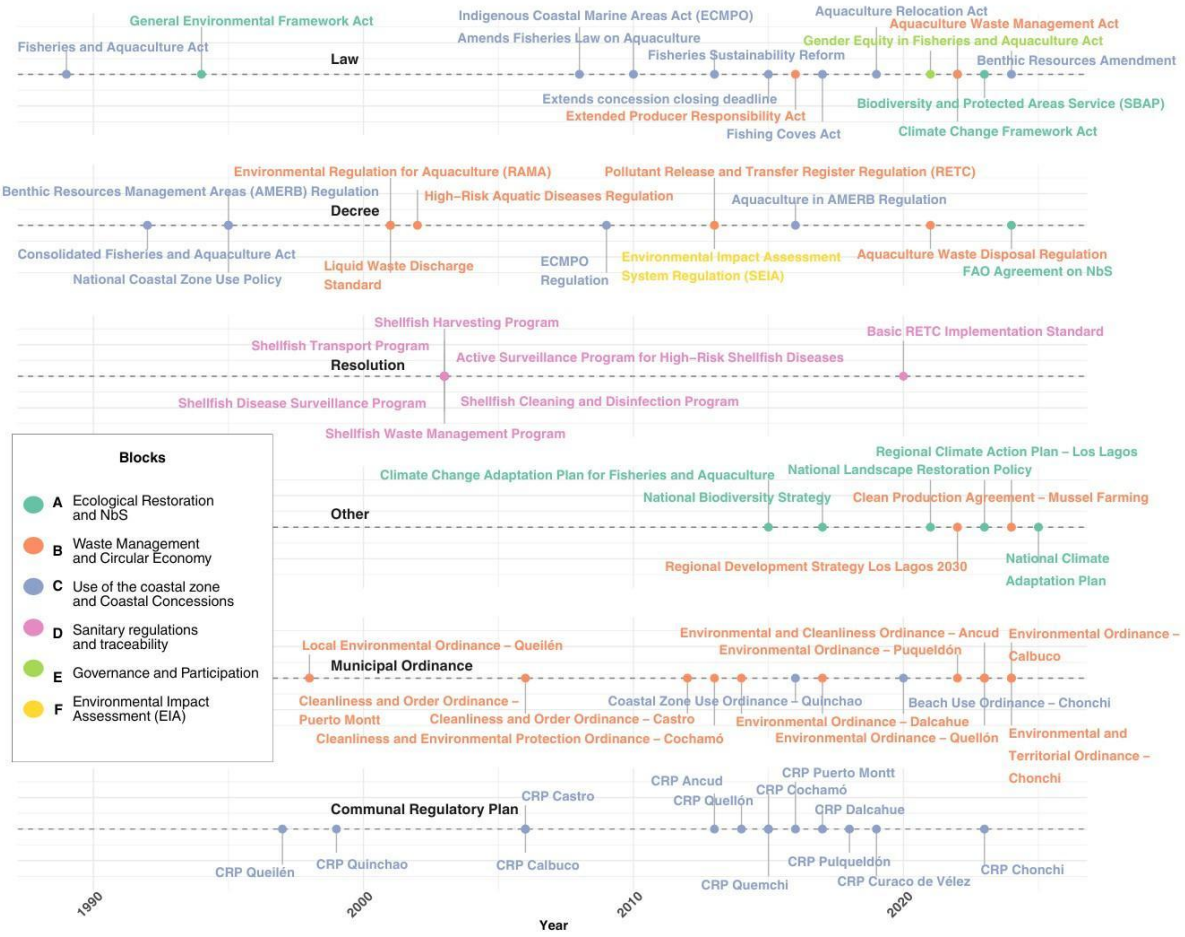


**Figure 2. Chronological evolution of Chilean legal instruments related to shell reuse (1989–2024).** This timeline includes 33 national regulations (laws, decrees, and resolutions), 7 other national and regional policy instruments (strategies, action plans, and governance agreements), and 26 subnational instruments from the Los Lagos Region (municipal ordinances and communal regulatory plans). These are classified into six policy domains or regulatory blocks: ecological restoration (A), waste management and circular economy (B), coastal use and concessions (C), sanitary regulations(D), governance (E), and Environmental Impact Assessment (F). It reflects a gradual policy shift toward sustainability, climate adaptation, and resource valorization.

While national-level legal instruments structure the formal regulatory architecture, the governance landscape is further shaped by subnational instruments.These instruments do not

293 modify the legal hierarchy of national regulations, nor do they independently authorize shell
294 reuse. However, their review reveals a consistent pattern of contextual ambiguity at the local
295 level. These exhibit temporal variation but limited thematic evolution. Municipal ordinances
296 are concentrated from the early 2000s onward increasing between 2012 and 2024 focused on
297 environmental management and sanitation. PRCs span 1997–202 centred on land-use planning,
298 urban development, and general coastal zoning. None of the reviewed subnational instruments
299 address marine restoration or shell waste valorization; where provisions exist, they rely on
300 broad or undefined categories that defer regulatory definition to higher-level legal frameworks.

301 **3.2 Regulatory Challenges to Shell Valorization**

302 Despite the progressive expansion of sustainability-oriented policies, significant regulatory
303 barriers persist for innovative initiatives that seek to reuse mussel shells for benthic restoration
304 and artificial reef creation. Under the current legal regime, mussel shells , although non-toxic,
305 are classified as aquaculture waste. The Supreme Decree No. 320 (RAMA; Environmental
306 Regulation for Aquaculture) prohibits the disposal of such waste into the sea, thereby
307 preventing its use in marine restoration.

308 This classification poses a legal paradox: although shell materials offer ecological benefits
309 [11,35] and align with circular economy principles, they are treated as organic waste. As a
310 result, initiatives intending to use these biogenic materials for restoration must navigate a
311 fragmented and restrictive legal system that lacks specific protocols, recognition mechanisms,
312 and permitting pathways.

313 Moreover, no current regulation differentiates shell waste from other waste streams, nor does
314 any formally recognize them as a “valorized subproduct”. Their use is not explicitly integrated
315 into environmental planning tools like the Environmental Impact Assessment System (EIA),
316 which increases legal uncertainty and operational risk for proponents

317 The regulatory ecosystem for mussel shells valorization spans multiple ministries and agencies,
318 including Undersecretariat of Fisheries and Aquaculture (SUBPESCA), National Fisheries and
319 Aquaculture Service (SERNAPESCA), the Ministry of Environment (MMA), Biodiversity and
320 Protected Areas Service (SBAP), and the Ministry of Health, without a coordinated
321 implementation mechanism. This institutional fragmentation generates procedural bottlenecks
322 [36], especially for pilot or experimental initiatives that fall outside conventional project
323 categories.

324 Legal instruments often operate in silos, and projects must comply simultaneously with
325 fisheries, environmental, territorial, and sanitary regulations, each managed by different
326 authorities. This disjointed governance landscape significantly hampers innovation and slows
327 down the deployment of nature-based solutions at scale.

328 Taken together, restrictive instruments do not operate in isolation but form a coherent and
329 mutually reinforcing regulatory block grounded in solid waste control and sanitary risk
330 avoidance. Environmental, sanitary, and emission regulations converge in framing mussel
331 shells exclusively as waste or potential secondary contaminant, regardless of their biogenic
332 properties or restoration potential. Even recent legal updates that introduce environmental
333 recovery obligations (e.g., Law 21.410), shell material remain embedded within this waste-
334 control paradigm and do not create legal pathways for valorization or marine reuse. As a result,
335 regulatory barriers to shell reuse are not the product of a single prohibitive rule, but of
336 cumulative and overlapping restrictions that systematically privilege risk containment over
337 ecological restoration.

338 **3.3 Distribution of Regulatory Functions Across Policy Blocks and Governance Levels**

339 To synthesize how Chile's regulatory framework constrains or enables mussel shell reuse in
340 marine restoration, we aggregated all coded legal instruments by policy domain blocks, legal

function, and governance level (Figure 3). This aggregation provides an overview of the institutional balance between enabling, ambiguous, and restrictive regulations shaping the governance landscape for shell reuse.

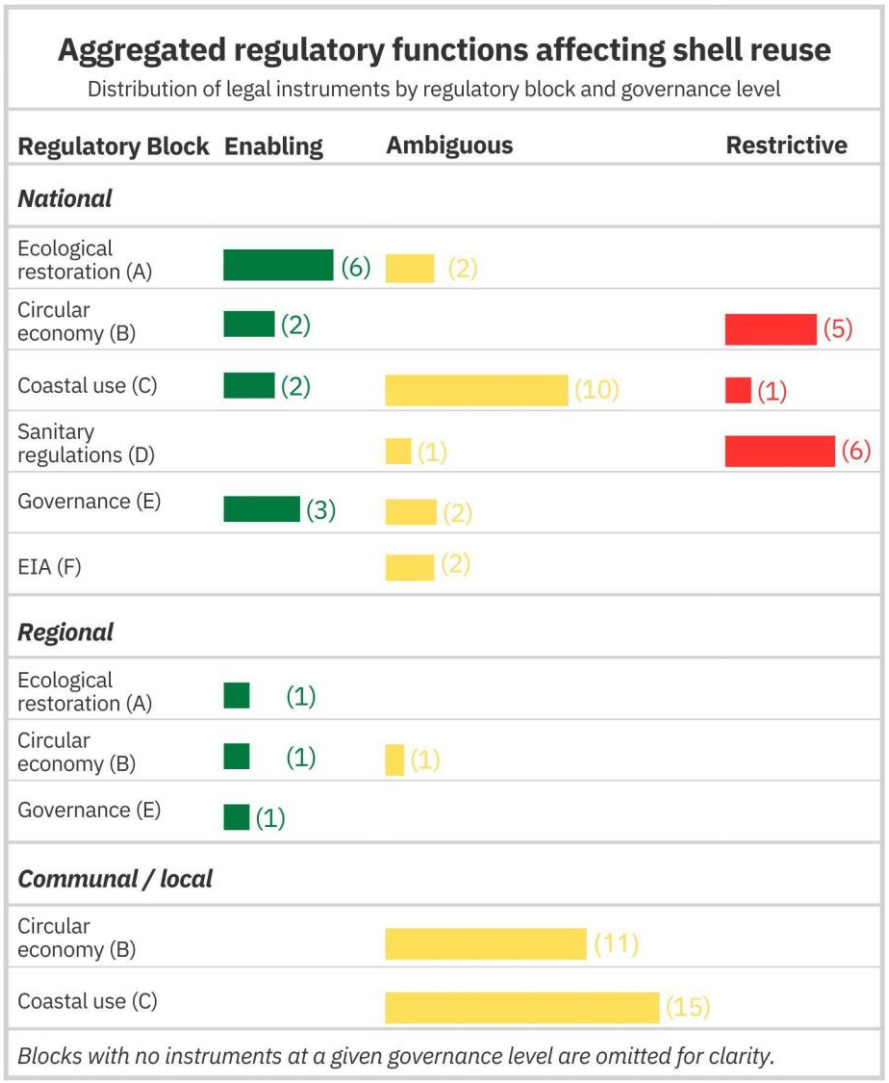


**Figure 3. Aggregated regulatory effects on shell reuse across governance blocks and levels.** The figure shows the number of legal instruments with enabling (green), restrictive (red), and ambiguous (yellow) effects on shell reuse, aggregated by regulatory block and disaggregated by governance level (national, regional, and communal/local). Bar length represents the relative concentration of instruments within each block, with exact counts shown in parentheses. Regulatory blocks are defined as follows: A = Ecological restoration and nature-based solutions (NbS); B = Waste management and circular economy; C = Coastal zone

use and coastal concessions; D = Sanitary regulations and traceability; E = Governance and participation; F = Environmental Impact Assessment (EIA). Blocks with no instruments at a given governance level are omitted for clarity.

Figure 3 summarizes these distributions across national, regional, and communal/local levels, revealing marked asymmetries both across policy domains and scales of governance. While enabling provisions exist, the overall regulatory architecture is dominated by restrictive and ambiguous instruments, particularly at higher levels of legal authority.

**Restrictive instruments and friction points**

Restrictive regulations are concentrated primarily at the national level, particularly within Block B (Waste Management and Circular Economy) and Block C (Use of the Coastal Zone and Concessions). Foundational instruments such as the Regulation on Aquaculture Environmental Management (RAMA; Supreme Decree No. 320/2001) primarily regulates the environmental impacts of aquaculture activities by setting thresholds for waste discharges. Within this framework, the regulation does not explicitly differentiate between waste streams derived from salmon farming and mussel farming, despite their contrasting biophysical characteristics and environmental dynamics. In this instrument, mussel shells are implicitly treated as waste, which constitutes a hard regulatory barrier that effectively precludes their reuse in marine restoration contexts, regardless of potential ecological benefits.

As illustrated in Figure 4C, restrictive instruments cluster around specific legal types—most notably decrees and exempt resolutions—and are unevenly distributed across regulatory blocks. This concentration amplifies their practical effect, as high-level prohibitions tend to override more recent policy signals promoting valorization or circular economy principles, such as the National Climate Change Adaptation Plan [37]. The resulting interaction between

restrictive waste classifications and emerging sustainability mandates generates persistent institutional friction points that discourage innovation and raise procedural risks for nature-based solutions relying on shell material.

**Ambiguous instruments and grey zones**

A substantial share of the regulatory framework is characterized by ambiguity, particularly within Block C (Coastal use), Block A (Ecological Restoration and Nature-based Solutions) and Block F (EIA) (Figures 3 and 4B). These instruments neither explicitly authorize nor prohibit shell reuse, leaving key implementation decisions to discretionary interpretation by regulatory authorities.

EIA regulations exemplify this grey zone. Although shell-based restoration projects do not fit neatly within traditional project typologies, there are no explicit thresholds or technical criteria defining when such initiatives trigger environmental assessment. As shown in Figure 4B, ambiguity dominates across multiple legal instrument types, reinforcing case-by-case decision-making and generating uncertainty for project proponents.

In regional and local/communal regulations, ambiguity outweighs explicit restriction (Figure 3), reflecting their subsidiary, implementation-oriented role within Chile's legal hierarchy. While they do not explicitly address the reuse of marine shells, they do influence its local implementation through land-use designations and planning instruments.

**Enabling instruments and missed opportunities**

Explicitly enabling instruments are comparatively scarce and unevenly distributed across policy blocks and governance levels (Figure 3). Framework laws such as the Climate Change Framework Law (Law 21.455) and the law establishing the Biodiversity and Protected Areas Service (SBAP; Law 21.600) formally recognize ecological restoration and nature-based

solutions as legitimate policy objectives. These instruments constitute key enabling anchors for shell reuse in restoration initiatives. In addition, instruments classified as "other"—including national policies and plans such as the National Landscape Restoration Policy and the National Climate Change Adaptation Plan—function as enabling but non-binding policy tools. These instruments guide public and private action by setting priorities, but do not create enforceable obligations. They remain relevant by aligning policy and funding for pilot projects and sectoral programs, while providing a soft enabling context for future regulatory development.

However, Figure 4A shows that enabling provisions are numerically outweighed by restrictive and ambiguous instruments operating in adjacent regulatory domains. In the absence of harmonized technical standards, clear classification criteria for biogenic materials, and coordinated permitting mechanisms, the enabling potential of these laws remains largely symbolic rather than operational. This imbalance results in missed opportunities, where high-level policy commitments to restoration and circular economy are not translated into implementable governance pathways.

Figures 3 and 4 reveal a regulatory architecture tilted toward restriction and ambiguity rather than explicit enablement. Barriers to shell reuse arise not only from formal prohibitions, but from the cumulative interaction of restrictive waste classifications, ambiguous procedural rules, and fragmented governance across policy blocks and levels. Addressing these patterns will require targeted clarification of grey zones, reinterpretation of restrictive classifications, and the operationalization of existing enabling mandates to unlock the potential of mussel shell reuse within marine nature-based solutions.

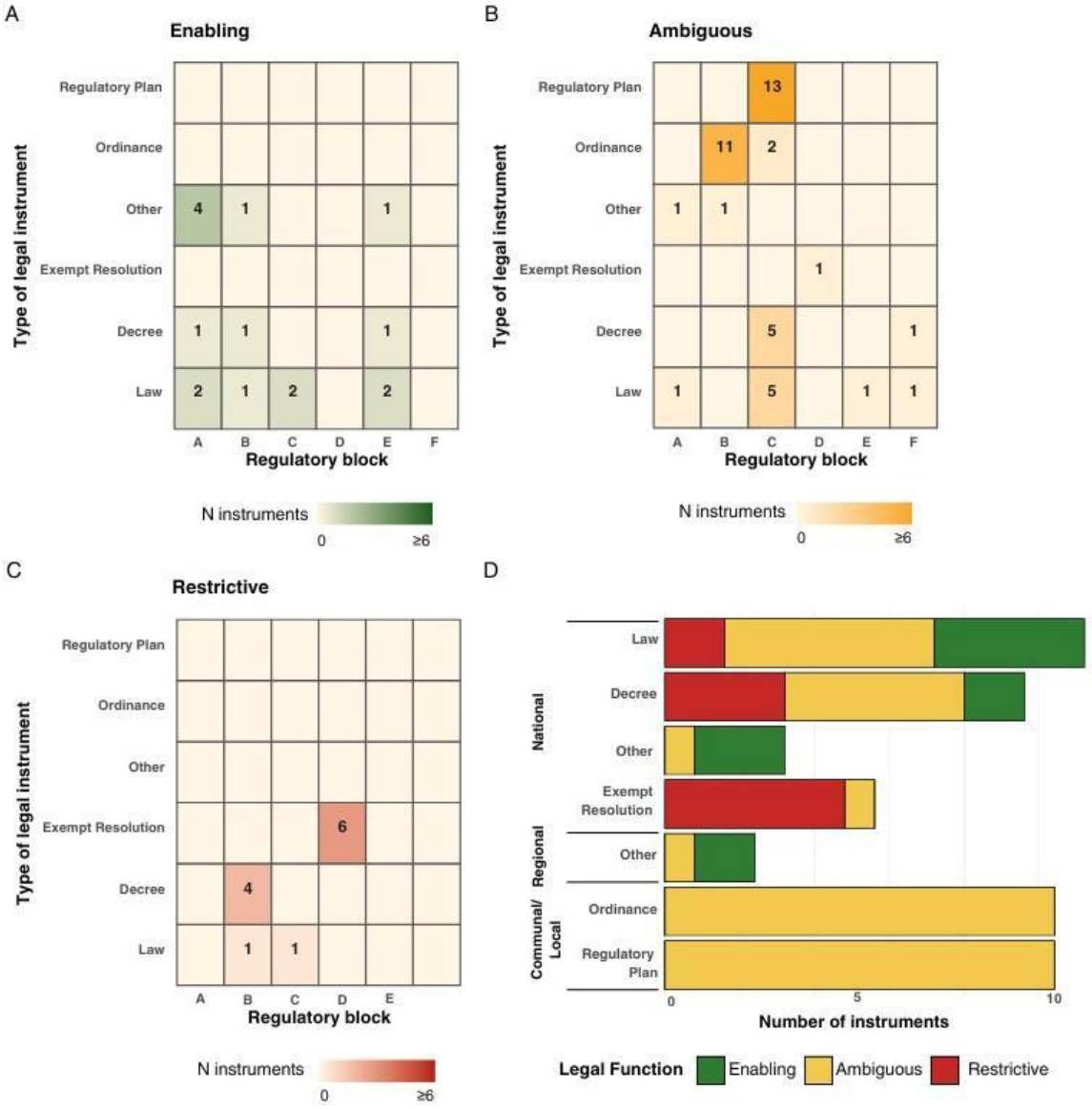


**Figure 4. Regulatory structure affecting shell reuse in Chile.** Panels A–C show the distribution of enabling, ambiguous, and restrictive legal instruments across regulatory blocks (A-F) and types of legal instruments. Colour intensity represents the number of instruments within each cell. Panel D summarizes the distribution of legal functions across governance levels. Together, the figure highlights the concentration of ambiguity at the communal level and the coexistence of enabling and restrictive instruments at the national level.

### 3.4 Workshop Insights and Stakeholder Perspectives

The participatory workshop held in June 2025 in Castro, Chiloé, grounded the legal analysis in practice. Structured around five thematic axes aligned with the study's policy domains, the workshop convened 50 stakeholders from public institutions, aquaculture companies, academia, and local communities. The resulting co-produced matrix (Table 1) offered a diagnosis of regulatory gaps and institutional bottlenecks, together with practical and context-sensitive recommendations.

**Table 1.** Co-produced Regulatory Matrix from Participatory Workshop. It summarizes regulatory gaps, opportunities, recommendations, and key observations for five thematic axes relevant to the reuse of mussel shells in marine ecological restoration. The matrix reflects stakeholder inputs across sectors and is organized according to the analytical framework guiding this study.

| Theme | Regulatory Gaps | Opportunities | Recommendations | Observations |
|---|---|---|---|---|
| Ecological Restoration and Nature-based Solutions (NbS) | General lack of awareness about shell-related challenges and solutions; unclear regulations and concepts around 'waste' and 'residue'; legal differences between land (private) and marine | Develop regulations inspired by agricultural lime practices; involve communities through education and participation; foster coordination within the aquaculture sector. | Build social license through communication, community engagement, perception studies, and environmental education; align public-private incentives for restorative practices; adopt an ethical, community-centered lens. | Ethical perspective: 'give back' to those who have historically cared for coastal ecosystems. |

| | | | | |
|---|---|---|---|---|
| | (public) shell disposal. | | | |
| Waste Management and Circular Economy | No institution with a clear mandate to authorize marine shell reuse; regulatory ambiguity on shell classification as waste; limited public knowledge on alternative uses. | Legally define shells as by-products; promote their use in ecological restoration; create an interinstitutional working group; modify RAMA (Decree 320); draft a specific shell reuse manual. | Establish shell reuse project categories based on positive environmental impacts; explore new economic and ecological applications; strengthen involvement of maritime and sectoral authorities. | Environmental and social value of shell reuse must be better recognized to unlock economic potential. |
| Coastal Use and Concessions | Unclear rules and tensions around the Lafkenche Law; excessive permitting times; challenges in implementing coastal use norms. | Use the Caletas Law to integrate shell reuse into coastal plans; plan beach-use zones; promote prevention of waste generation; create a public coastal cleanup registry. | Encourage compliance through monitoring and cultural change; integrate shell disposal into spatial planning; implement public access beach-use planning tools. | Compliance remains primarily sanction-driven; a shift toward stewardship culture is needed. |
| Sanitary Regulations and Traceability | Legal classification of shells as waste restricts alternative uses; limited engagement of key public agencies; communities unaware of ecological and | Reclassify shells as a valorized by-product; draft a management plan for safe reuse; engage agencies like SAG, Health, SMA, and regional government in a formal network. | Amend Decree 320 to permit alternative uses; include shell reuse in Decree 64; support Clean Production Agreements (APL); establish organic matter thresholds to facilitate regulatory acceptance. | Technical specifications (e.g., organic matter thresholds) could support broader acceptance. |

| | | | | |
|---|---|---|---|---|
| | social benefits of shell reuse. | | | |
| Governance and Participation | Rigid interpretation of RAMA (Decree 320); fragmented legal frameworks; lack of institutional responsibility; absence of pilot experiences to guide governance. | Reinterpret RAMA to reflect manufacturing waste origin; highlight cross-sectoral benefits; involve the regional government and CRUBC in leading a pilot plan; connect with climate policies. | Promote pilot restoration projects led by CRUBC; clearly assign institutional responsibilities; include small aquaculture operators and encourage infrastructure built with enhanced shell materials; inform the public of the benefits of shell reuse. | Pilot projects are needed to measure and demonstrate the multi-benefit value of shell-based restoration. |

A key barrier consistently identified by participants was the lack of regulatory clarity regarding marine disposal and restoration uses of shell material, particularly stemming from the rigid interpretation of Supreme Decree No. 320 (RAMA). The legal but implicit classification of mussel shells as "waste" of the aquaculture industry was widely perceived as a hard regulatory barrier, preventing their reuse despite evidence of their ecological value as biogenic substrates.

Discussions highlighted that overcoming these barriers may not require legislative reform, but rather reinterpretation and coordination of existing instruments. Stakeholders noted that RAMA allows interpretive space to distinguish between polluting residues and restoration-grade materials (e.g., cleaned and processed shells). Similarly, the Extended Producer Responsibility Law (Law 20.920) was identified as a potential core enabling lever for reclassifying shell waste as a valorized subproduct, albeit one that currently lacks technical guidance and inter-institutional coordination mechanisms for implementation.

Several stakeholders drew parallels with the terrestrial use of agricultural lime, highlighting inconsistencies in how analogous materials are regulated across land and sea and revealing a structural disconnect between land-based and marine regimes, particularly in the definitions of "waste" and "valorized subproducts". Participants highlighted the lack of technical criteria to distinguish shell residues destined for disposal from those suitable for restoration (e.g., cleaned, sorted shells with low organic content). In their absence, shell materials are treated as contaminants, reinforcing regulatory ambiguity and discretionary decision-making.

Beyond legal classifications, institutional fragmentation was identified as a major operational barrier. Stakeholders expressed frustration over the absence of a clearly mandated institutional lead to authorize shell reuse in marine environments. Projects must navigate overlapping and sometimes contradictory responsibilities across sectors responsible for aquaculture, environmental, biodiversity, public health, and maritime authority, among others, creating procedural delays and limiting space for pilot innovation. This fragmentation mirrors the regulatory friction identified in the document analysis.

Notably, participants emphasized social legitimacy as a key condition for advancing shell reuse initiatives. Reintroducing shells to the sea was framed not only as a technical intervention but as ecological restoration and cultural reparation grounded in reciprocity between coastal communities and marine ecosystems. Stakeholders called for participatory monitoring, environmental education, and inclusive pilot projects that recognize the knowledge and agency of local communities and small-scale aquaculture producers.

The Clean Production Agreement (APL), recently committed by the mussel industry [38], was highlighted as a promising platform for public–private collaboration and experimentation, capable of incubating pilot initiatives within existing regulatory constraints. Regional policy instruments—such as the Regional Climate Change Adaptation Plan—were also identified as

underutilized spaces where shell reuse could be aligned with broader climate resilience and sustainability objectives.

Overall, the workshop confirms that regulatory transformation can begin through reinterpretation, coordination, and demonstration, rather than awaiting formal legal reform. The co-produced recommendations summarized in Table 1 provide actionable pathways to improve legal coherence, operationalize existing enabling mandates, and strengthen the social legitimacy of marine restoration initiatives based on circular use of aquaculture residues (Figure 5).

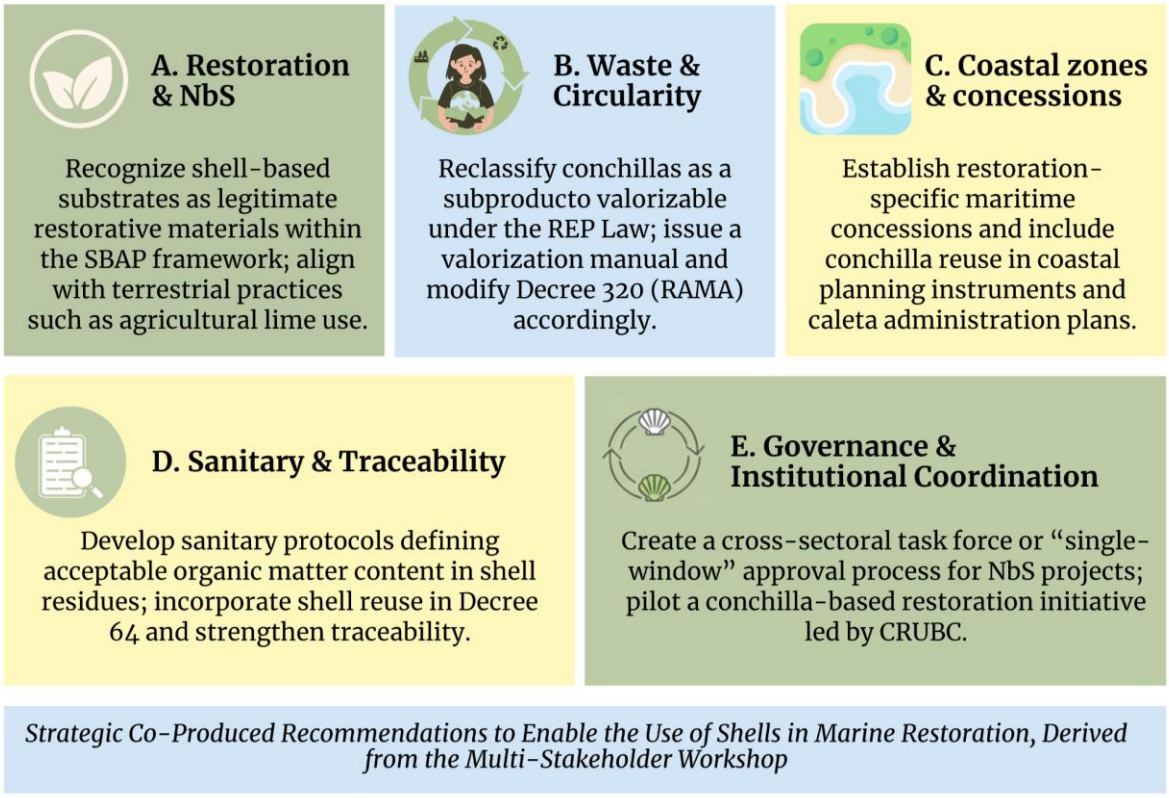


**Figure 5. Strategic co-produced recommendations to enable the reuse of shell residues in marine restoration, derived from the multi-stakeholder workshop held in Castro, Chile, in June 2025**. These recommendations aim to reinterpret existing legal frameworks, coordinate

institutional responsibilities, and create enabling conditions for pilot innovation and participatory restoration practices**.**

## 4. Discussion

The main finding of this study is not regulatory absence, but regulatory misalignment: a legal architecture that privileges waste control and sanitary risk avoidance over restoration-oriented innovation [39,40]. This misalignment emerges from the interaction of pollution-control logics, procedural ambiguity, and fragmented institutional mandates across environmental, productive, and territorial sectors [41].

Within this architecture, two regulatory levers emerge as particularly strategic for enabling shell reuse in coastal restoration: (1) the reinterpretation of Decree 320 (RAMA), which currently prohibits the marine deposition of aquaculture residues regardless of ecological purpose; and (2) the activation of valorization mechanisms under the Extended Producer Responsibility Law (Law 20.920), which could allow mussel shells to be reclassified as restoration-grade by-products rather than waste.

These entry points offer the most immediate pathway for advancing circular restoration within the existing legal framework, based on structured reinterpretation, technical guidance, and pilot-based validation. Other regulatory domains—such as sanitary protocols, EIA procedures, and coastal concession regimes—remain relevant, but their enabling potential depends largely on how these two core levers are operationalized and coordinated.

We acknowledge that reinterpretation is not without legal limits [42]. In formalized administrative systems such as Chile's, reinterpretation must be anchored in explicit technical criteria, formal guidance, and procedural safeguards to avoid arbitrariness or legal challenge [43,44]. Accordingly, our argument is for institutionally sanctioned reinterpretation supported

by inter-agency coordination, pilot protocols, and clear technical standards [41,45]. Such reinterpretation processes are likely to face institutional inertia, legal conservatism, and resistance from risk-averse authorities, highlighting the importance of incremental, well-documented pilot initiatives capable of withstanding administrative and judicial scrutiny [36,46,47]. These challenges are not unique to Chile, but reflect broader international patterns observed in early regulatory adaptation to nature-based solutions using marine biogenic materials.

### 4.1 International Comparisons: Lessons from Australia, the United States, and Japan

Regulatory guidance from Australia [13,48], the United States [49,50], and Japan [51,52] provide conceptual benchmarks that help interpret Chile's regulatory challenges. These examples illustrate governance design features that have enabled shell-based restoration abroad.

First, these jurisdictions formally recognize shell placement as a legitimate restoration activity. In the United States, Nationwide Permit 27 under the Clean Water Act explicitly authorizes shell and biogenic material placement for habitat enhancement. The National Oceanic and Atmospheric Administration (NOAA) and the U.S. Army Corps of Engineers (USACE) provide detailed guidance on ecological justification, monitoring, and permitting pathways. In Australia, state-level Shellfish Reef Restoration Guidelines —most notably from New South Wales [48] and the Department of Agriculture, Water, and the Environment [13]—outline when and how cleaned or cured shell may be deployed in coastal waters, specifying biosecurity, curing time, and environmental safeguards.

Japan's Ministry of Agriculture, Forestry and Fisheries and the Japan Fisheries Agency likewise authorize the use of mollusk shells and calcareous substrate for benthic enhancement under national aquatic animal health protocols [51]. These examples contrast with Chile, where

D.S. 320/2001 maintains a blanket prohibition on marine deposition of aquaculture residues regardless of purpose.

Second, enabling jurisdictions to differentiate "restoration-grade" shells from raw waste through science-based technical standards [53]. U.S. federal guidance distinguishes raw discarded shells from processed material suitable for ecological restoration, specifying resting periods, organic-load thresholds, and sanitary quality criteria [49,50]. Australia and Japan also employ risk-based standards that determine whether shell material can be safely repurposed [13,54,55]. Chile lacks such functional differentiation, retaining a single legal category of "aquaculture waste" that restricts restoration use even when the shell has been cleaned, sorted, or cured.

Third, coordinated permitting reduces fragmentation and ensures consistent interpretation. In the United States, NOAA, Environmental Protection Agency (EPA), and USACE collaborate in the permitting and oversight of shell-based restoration projects. Several states (e.g., Maryland, Louisiana) run shell-recycling programs that supply restoration-grade material and streamline logistics. Australia uses multi-agency review platforms that integrate fisheries, environmental, and biosecurity authorities [56]. Japan implements restoration activities largely through Fisheries Cooperative Associations supported by national technical guidance, creating predictable governance pathways [55]. In contrast, Chile's responsibilities are dispersed across SUBPESCA, SERNAPESCA, SEA, SEREMIs, and the Maritime Authority, contributing to the discretionary and fragmented interpretation identified in our results.

Taken together, these international examples illustrate how regulatory transformation can emerge not from new legislation, but from reinterpretive clarity, purpose-driven classification of biogenic materials, and coordinated institutional arrangements [13,53,54]. Rather than serving as blueprints for direct transplantation, they highlight governance design principles—

560 risk-based differentiation, coordinated permitting, and technical standard-setting—that can be
561 adapted to Chileans legal and institutional context.

562 **4.2 Bridging Governance Fragmentation**

563 Unlike the coordinated permitting mechanisms seen in the United States or the interagency
564 approaches in Australia, Chile's institutional framework is fragmented across SUBPESCA,
565 SERNAPESCA, SBAP, the Ministry of Health, SEA, and the Maritime Authority. This
566 fragmentation impedes clear guidance for proponents of restoration projects and limits
567 institutional learning across sectors.

568 Establishing a unified coordination platform—through Clean Production Agreements, regional
569 climate adaptation plans, or a cross-sectoral NbS task force—could help integrate shell reuse
570 into national policy agendas. Regional governance arenas may be particularly well positioned
571 to act as regulatory laboratories, where interpretive flexibility, local knowledge, and pilot-
572 based experimentation can be aligned under national mandates [43,45].

573 EIA-related uncertainty emerges as a key cross-cutting constraint. There is no clear project
574 typology distinguishing shell-based restoration from aquaculture or waste management, nor
575 defined thresholds to determine when environmental assessment is required [41,57,58]. As a
576 result, projects fall into a regulatory grey zone, subject to case-by-case interpretation. This
577 contrasts with evidence showing that shell-based restoration poses low ecological risks when
578 appropriate preparation and monitoring protocols are applied, while generating measurable
579 ecosystem services [53,59,60].

580 As noted during the participatory workshop, this discretionary implementation creates legal
581 and operational risk for pilot initiatives, which may face disproportionate requirements, delays,
582 or even outright rejection due to the lack of regulatory precedent. The absence of technical

criteria—especially to distinguish between hazardous waste and cleaned, restoration-grade shell material—exacerbates this uncertainty. Addressing this bottleneck requires the development of technical guidelines, the creation of a specific typology for circular restoration projects, and the adoption of more risk-proportionate evaluation procedures that reflect the low ecological risks and potential benefits of such interventions.

### 4.3 Toward an Enabling Framework for Circular Restoration

Chile's case suggests that reinterpretation, interagency coordination, and pilot-based regulation may offer a more feasible—and politically viable—pathway than comprehensive legislative reform. This approach enables context-sensitive experimentation in risk management while operating within existing legal frameworks [41,43].

Workshop findings further indicate that regulatory transformation must be both technically robust and socially legitimate. Embedding restoration initiatives within local cultural values and participatory monitoring schemes can enhance ecological outcomes while strengthening public trust. In this context, shell reuse offers a strategic entry point to integrate gender-sensitive and Indigenous governance considerations into marine restoration policy [53,54]. Illustrative cases such as the "Shuck Don't Chuck" program in Port Phillip Bay (Australia) show how shell recycling—through partnerships among public agencies, private actors, and local and Indigenous communities—can support reef restoration while embedding community participation across collection, restoration, and monitoring processes, thereby fostering shared responsibility and social legitimacy [13,61,62].

Workshop discussions revealed that regulatory uncertainty and procedural complexity disproportionately affect small-scale aquaculture producers, who often lack the capacity to navigate fragmented permitting systems. Rather than treating gender and equity as ancillary concerns [63], shell reuse initiatives offer a pathway to embed inclusion, local knowledge, and

607 distributive justice within emerging regulatory frameworks [5,64,65]. Integrating participatory
608 monitoring, co-designed pilots, and gender-sensitive criteria could strengthen social legitimacy,
609 regulatory effectiveness, and ecological outcomes [66–68], while opening avenues for future
610 research on more inclusive governance through circular marine restoration.

611 However, reinterpretation and coordination alone are insufficient without matching
612 institutional capacity. The feasibility of shell reuse depends on adequate staffing, monitoring
613 resources, and clear accountability for enforcement and technical oversight [27,69,70]. Current
614 limitations constrain agencies' ability to implement new procedures or oversee pilot initiatives.

615 Moreover, without a baseline monitoring system or traceability tools for reused shell material,
616 there is a risk of regulatory evasion or reputational backlash if projects are perceived as
617 greenwashing or improper waste disposal [70]. This reinforces the need not only for legal
618 clarification but also for investment in institutional infrastructure, including training programs,
619 inter-agency communication protocols, and participatory monitoring mechanisms. Without
620 these, policy shifts may remain rhetorical rather than transformative.

621 As highlighted in the workshop, advancing shell reuse in marine restoration is not only a legal
622 or technical challenge but also a cultural and ethical one. Participants framed restoration as a
623 form of socio-ecological reparation in territories shaped by extractive aquaculture, highlighting
624 the importance of rebuilding relationships between communities and marine ecosystems.

625 This insight resonates with broader scholarship on relational values, biocultural restoration,
626 and environmental justice, which stress the need to embed nature-based solutions within local
627 worldviews, practices, and value systems [71–73]. In regions like Chiloé island, where small-
628 scale aquaculture, cultural identity, and marine stewardship are deeply intertwined, social
629 legitimacy may determine the success or failure of restoration efforts. To that end, restoration

strategies should prioritize community engagement, participatory monitoring, and intercultural dialogue as foundational, not ancillary, components of policy innovation.

### 4.4 Study limitations

This study is subject to several limitations. First, the policy mapping relies on publicly available legal and regulatory instruments and may not fully capture emerging administrative practices, internal technical guidelines, or informal interpretations used by regulatory agencies. Second, while the participatory workshop included a diverse set of actors from government, aquaculture, academia, and local communities, it does not represent the full spectrum of institutional positions—particularly those of national-level authorities whose decisions shape regulatory implementation. In addition, this analysis focuses on regulatory design and stakeholder perspectives rather than on the empirical evaluation of implemented shell-based restoration projects. This reflects the analytical scope of the present study. Empirical research on shell-based restoration—including ecological performance, monitoring protocols, and socio-ecological outcomes of pilot interventions—is being conducted in parallel through ongoing field-based and experimental initiatives, which lie beyond the remit of this article.These limitations highlight areas where further research is needed, including interviews with national regulators, longitudinal assessments of pilot initiatives, and deeper comparative examination of regulatory reforms in other jurisdictions.

### 4.5 Policy pathways for enabling circular marine restoration

Taken together, these findings point to a set of pragmatic, policy-relevant actions that can enable circular marine restoration within existing regulatory systems. Rather than calling for legislative reform, the Chilean case highlights how targeted regulatory clarification and coordination can translate high-level commitments to restoration and circular economy into operational pathways. These pathways reflect broader insights from the policy mix literature,

654 which emphasizes coordination, sequencing, and reinterpretation of existing instruments over
655 single-instrument reform [41].

656 Specifically, enabling shell reuse in marine restoration requires: clarifying the functional
657 classification of biogenic materials, distinguishing restoration-grade shells from polluting waste
658 streams; issuing technical standards that define sanitation, curing, and traceability requirements
659 for restoration-grade shell material; coordinating competent agencies through pilot platforms
660 or inter-institutional agreements that reduce procedural fragmentation and regulatory
661 uncertainty; and embedding participation, monitoring, and social legitimacy from the outset to
662 ensure accountability, learning, and public trust. Building on these insights, we propose the
663 concept of shell-based socio-ecological restoration as an integrative framework to guide the
664 reuse of mussel shell waste in marine environments. This approach recognizes shells not only
665 as a biogenic substrate capable of enhancing habitat complexity and ecosystem functioning, but
666 also as a vehicle for fostering social legitimacy, cultural reciprocity, and participatory
667 governance. By bridging ecological processes with community-based practices and circular
668 economy principles, this framework provides a pathway to overcome existing regulatory
669 constraints and unlock the potential of shell waste as a nature-based solution.

670 **5. Conclusion**

671 In Chile, constraints to mussel shell reuse stem not from regulatory absence, but from a
672 misalignment between legacy waste frameworks and emerging restoration and circular
673 economy agendas. Addressing this gap does not require comprehensive legal reform; rather, it
674 can be advanced through the strategic reinterpretation and coordination of existing
675 instruments—particularly Decree 320 (RAMA) and the Extended Producer Responsibility
676 framework—to enable the reclassification of shells as restoration-grade resources.
677

Three priorities emerge to operationalize this pathway: (i) establishing a functional classification that distinguishes restoration-ready shells from waste; (ii) developing technical standards to ensure environmental safety, including protocols for treatment, curing, and traceability; and (iii) strengthening inter-institutional coordination to reduce fragmentation and support coherent permitting processes. At the same time, long-term viability depends on embedding restoration within local socio-ecological contexts and ensuring social legitimacy through community participation and local knowledge.

Beyond the Chilean case, these findings contribute to broader debates in marine policy and sustainability transitions by showing that meaningful innovation can emerge within existing legal systems through reinterpretation, administrative coordination, and pilot-based learning. This provides a pragmatic and transferable governance pathway to advance circular nature-based solutions, one that is both readily applicable and transferable to other coastal contexts facing similar tensions between environmental protection, waste regulation, and restoration imperatives.

## Author Contributions

María José Martínez-Harms: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. Uranía Lavín: Data curation, Formal analysis, Visualization, Writing – review & editing. Daniela Sotomayor-Gerding: Data curation, Writing – review & editing. Begoña Peceño: Writing – review & editing. Nelson A. Lagos: Writing – review & editing.

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## Conflict of Interest

The authors declare no conflict of interest.

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**Supplementary Material**

## Appendix A. Reproducible Coding Protocol for Regulatory Mapping

This appendix documents the coding framework used to classify legal and policy instruments relevant to the reuse of mussel shells in marine restoration. The protocol was designed to ensure transparency, analytical consistency, and reproducibility across governance levels and regulatory domains.

### A1. Governance Level Classification

Each legal or policy instrument was assigned to a governance level based on its issuing authority and spatial scope. Classification followed the rules summarized in Table A1.

**Table A1. Governance level classification criteria**

| **Instrument type** | **Issuing authority / source** | **Governance level** |
|---|---|---|
| Law | National Congress (published in *Diario Oficial*) | National |
| Decree | Line ministries (e.g., Environment, Health) | National |
| Exempt resolution | National agencies (e.g., SERNAPESCA, SUBPESCA) | National |
| Regional plans | Regional governments or SEREMIs | Regional |
| Municipal ordinances, communal regulatory plans | Municipal governments | Communal / Local |

Municipal ordinances and communal regulatory plans were coded as **communal/local** instruments and analyzed exclusively as part of the *implementation context*. They were not treated as primary regulatory drivers at the national or regional level.

**A2. Legal Function**

Each instrument was assessed for its **legal function** with respect to the reuse of mussel shells in marine restoration or nature-based solutions. Coding followed a structured decision tree to ensure internal consistency.

**Decision logic**

1. Does the instrument explicitly allow, promote, or mandate the reuse of biogenic materials (e.g., shells) for restoration, circular economy, or environmental purposes?
   **Enabling**

2. Does the instrument explicitly prohibit, restrict, or criminalize the marine deposition or reuse of aquaculture by-products or waste?
   **Restrictive**

3. Is the instrument silent on shell reuse, relies on undefined categories, or depends on discretionary interpretation by authorities (e.g., EIA triggers, ambiguous definitions)?
   **Ambiguous**

**Table A2. Legal function definitions and examples**

| **Legal function** | **Definition** | **Illustrative examples** |
|---|---|---|
| Enabling | Provides a legal pathway or mandate for reuse, valorization, or restoration | Law 20.920 (REP Law); SBAP Law; Climate Change Framework Law |
| Restrictive | Explicitly prohibits marine reuse or treats shells strictly as waste or pollutants | RAMA (D.S. 320/2001); aquaculture waste control decrees |
| Ambiguous | Does not address shell reuse or allows multiple interpretations | EIA thresholds; early fisheries laws; outdated norms |

### A3. Practical Effect on Shell Reuse

Beyond formal legal intent, each instrument was classified according to its **practical effect** on shell reuse initiatives, drawing on document analysis and stakeholder insights from participatory workshops.

**Decision logic**

1. Is there no applicable regulation addressing a key requirement (e.g., permitting, classification, authorization)?
   **Regulatory gap**

2. Does the instrument overlap or conflict with other regulations, generating contradictions across sectors?
   **Friction point**

3. Does ambiguity in the instrument lead to discretionary, case-by-case, or uncertain implementation?
   **Grey zone**

**Table A3. Practical effect categories**

| Category | Definition | Example |
|---|---|---|
| Regulatory gap | Absence of a relevant legal or regulatory framework | No mechanism to approve shell use in marine restoration |
| Friction point | Contradictory mandates across instruments or sectors | REP Law enables valorization, while RAMA bans marine reuse |
| Grey zone | Legal ambiguity resulting in discretionary enforcement | EIA thresholds unclear for shell-based NbS projects |

### A4. Barrier Type: Analytical Synthesis

To support integrative analysis and visualization, instruments were further grouped into **higher-level barrier types** based on the combined assessment of legal function and practical effect. This synthesis step was analytical rather than normative and does not imply equivalence in legal hierarchy or binding force.

**Table A4. Barrier type classification**

| Barrier type | Analytical criteria |
|---|---|
| Hard regulatory barrier | Instruments that explicitly prohibit or legally block shell reuse, leaving no room for reinterpretation |
| Contextual friction | Instruments that indirectly constrain reuse through overlap, contradiction, or procedural complexity |
| Contextual background | Instruments that shape governance context without directly enabling or restricting reuse |
| Core enabling lever | Instruments that provide legal mandates or anchors that could actively support shell reuse if operationalized |

**Illustrative examples**

- *Hard regulatory barriers*: RAMA (D.S. 320/2001); sanitary resolutions
- *Contextual friction*: LGPA provisions; EIA regulations
- *Contextual background*: municipal ordinances; communal regulatory plans (PRCs)
- *Core enabling levers*: REP Law; SBAP Law; Climate Change Framework Law

This synthesis category was used exclusively for interpretative analysis and visualization (e.g., heatmaps and governance matrices). All coding decisions, classification rules, and examples are provided to enable replication or adaptation of the protocol in other national or sectoral regulatory contexts.

## Appendix B. Regulatory Dataset and Coding Matrix

This appendix provides the full regulatory dataset used in the analysis, supplied as an Excel file. The dataset contains the complete list of legal, policy, and local instruments reviewed, together with their coding across governance level, legal function, practical effect on shell reuse, and analytical barrier type.

Each row corresponds to one regulatory instrument, and all coding categories follow the definitions and decision rules described in Appendix A. This dataset is provided to ensure transparency and reproducibility of the regulatory mapping and analytical synthesis.