Governing the decline: clam fisheries and the challenges of decentralized management across the western Mediterranean and Gulf of Cádiz (Spain)

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Abstract

Over the past four decades, clam fisheries along Spain's Mediterranean and Atlantic coasts have exhibited significantly different ecological and governance trajectories. This study synthesises long-term landing data from 1993 to 2024 with a systematic review of regional legislation to explore how management frameworks influence the resilience of fisheries. In the northwest Mediterranean, which includes Catalonia, the Valencian Community, the Balearic Islands, and Murcia, fisheries have experienced synchronous declines, a consequence of overexploitation, fragmented governance, and reactive, top-down regulation. In contrast, Andalusia, encompassing both the Atlantic and Alboran Sea coasts, has demonstrated more resilient trajectories, bolstered by greater ecological productivity and the adoption of adaptive governance strategies since the 2010s. In this region, the implementation of gear-specific management plans, rigorous scientific monitoring (including satellite tracking), and prompt administrative responses have facilitated more sustainable exploitation. Our findings highlight the necessity of aligning governance with ecological connectivity and integrating adaptive co-governance structures that engage fishers to safeguard the future of small-scale fisheries. More broadly, this research emphasises the need for coordinated superregional or national management frameworks that incorporate ecological knowledge, promote stakeholder participation, and allow for timely regulatory adaptation.

Keywords:

Clam fisheries; stock decline; regional trends; management misalignment; adaptive management, Spain

1. Introduction

Marine fisheries are a key source of high-quality protein and play a central role in global food security, employment, and trade [1]. Since the mid-20th century, global demand for seafood has been growing steadily, driven by population growth, rising incomes, and increasing awareness of its health benefits [2]. However, wild marine fishery production has plateaued at around 90 million tonnes annually since the late 1980s [1]. Aquaculture has expanded rapidly to bridge the widening supply-demand gap, but in the European Union (EU), this imbalance is particularly critical. Over the past three decades, wild fisheries production has steadily declined, while seafood demand has continued to increase. Aquaculture output has remained relatively stable and insufficient to compensate this decline [3]. Consequently, the EU has become increasingly reliant on seafood imports [4]. This growing imbalance underscores the urgency of moving beyond fragmented management frameworks and adopting regionally coordinated approaches to secure local fisheries.

The decline in EU fisheries productivity is due to a complicated mix of regulatory, social, economic, and environmental factors. The key drivers are as follows: (1) Regulations: the EU's Common Fisheries Policy (CFP) has introduced stricter quotas and limits on fishing effort to address overfishing and protect fish stocks [5]; (2) Fleet decommissioning: EU and national governments have incentivised vessel scrapping as a means to align fleet capacity with available resources [6,7]; (3) Stock and ecosystem protection: scientific assessments have indicated stock declines due to historical overfishing, leading to restrictions such as marine protected areas (MPAs) and seasonal bans that have curtailed fishing opportunities [8]; (4) Rising operational costs, including fuel, maintenance, and labour, alongside fluctuating seafood market prices, have diminished profitability, prompting some operators to exit the sector [8,9]; (5) Technological advancements have improved vessel efficiency, allowing fewer boats to sustain catches, which has resulted in a structural reduction of fleet size [10,11]; (6) Global competition: increasing imports of cheaper seafood from non-EU countries have pressured profit margins and hastened fleet reductions [8,12]; finally, sociodemographic shifts: challenging working conditions, unstable incomes, and the availability of alternative job opportunities have rendered the profession less appealing to younger generations [6,13].

The small-scale fisheries (SSF) sector has seen the biggest drop in landings [14]. This sector makes up most of the Spanish fleet, with 64% of landings between 2006 and 2020 SSF typically involves vessels under 12 metres in length, operating in coastal and adjacent waters, manned by small crews, and employing diverse fishing gear and techniques on daily fishing trips. These fisheries often require a low initial investment and are generally owner-operated [15]. In contrast to industrial and semi-industrial fisheries, SSF demonstrates lower costs, catches, turnover, reliance on subsidies, and fuel consumption [16]. Despite their smaller scale, SSFs yield higher profits per investment, improved catch efficiency per litre of fuel, and greater socioeconomic value per kilogram of marine resources harvested [17]. Additionally, SSF play a vital role in providing employment, fostering local development, offering more equitably distributed economic benefits, and supplying fresh, high-quality seafood to local, regional, national, and international markets [18]. The sector also includes shore-based shellfishers who target sedentary and low-mobility species, such as clams, cockles, barnacles, and polychaetes, which are collected during low tide or in shallow waters less than 1.5 metres deep [19–22]

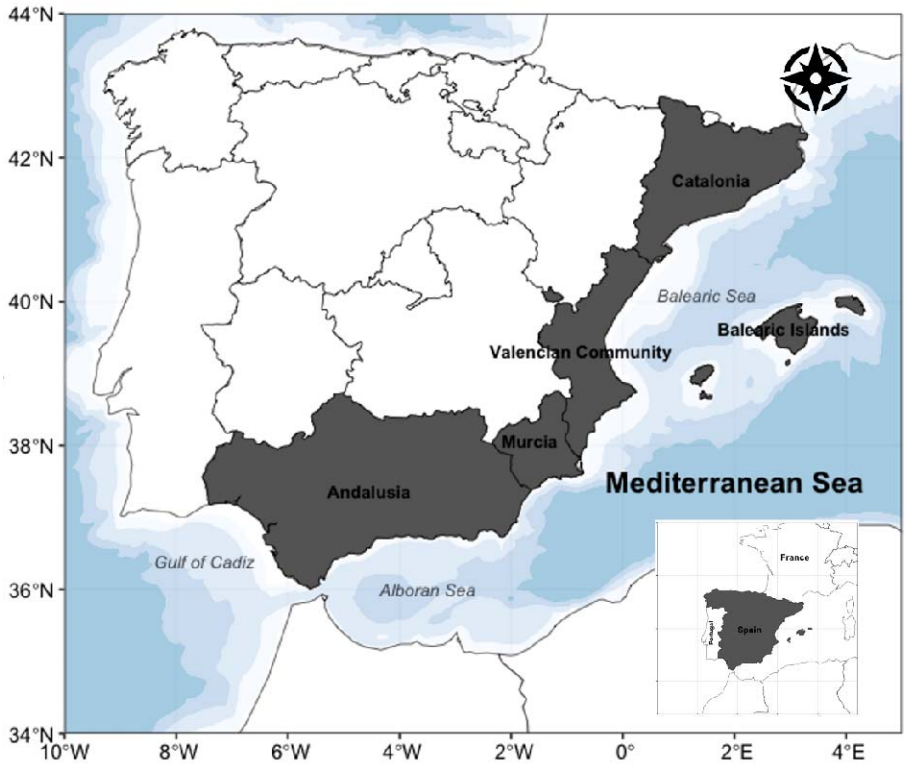

Figure 1. Map of the studying area, with the Autonomous Community where the main clam fisheries are located.

The decline in landings has been particularly dramatic in small-scale fisheries targeting commercial clams (e.g., *Donax trunculus*, *Chamelea gallina*, and *Callista chione*) along Spain's Mediterranean and southwest Atlantic coasts, particularly in Andalusia. Once a significant source of regional economic activity, buoyed by high clam landings during the 1990s, these fisheries now exist solely in Andalusia and Catalonia (see **Fig. 1**). These clam species are shallow-burrowing, suspension feeders, yet they inhabit different environments. *D. trunculus* thrives in highly dynamic sandy beaches typically in fine, well-sorted sands at depths of 0-2.5 metres [23]. In contrast, *C. gallina* inhabits a broader range of sediments, including sand, sandy mud, and mud, at depths of 3–20 meters [24]. *C. chione* prefers coarse sands at depths of 3-180 metres [25], although it is most abundant at depths of 5 and 30 metres in the Mediterranean Sea (Baeta et al., 2014). Traditionally, clam fisheries in this region have included five primary production systems: (1) vessel-based mechanised clam dredges operated by winches, which were once widespread in Catalonia, the Valencian Community, parts of the Andalusian Mediterranean, and previously in Murcia and the Balearic Islands, primarily targeting *D. trunculus*, *C. gallina*, and *C. chione*; (2) vessel-based mechanised clam dredges powered by engines, exclusively employed in deeper sandy areas of Andalusia, mainly targeting *C. gallina* and *D. trunculus*; (3) vessel-based towed dredges, found only in the Ebro Delta, Catalonia, targeting *C. gallina*; (4) vessel-based hydraulic clam dredges along the South Atlantic coast of Andalusia, also targeting *C. gallina*; and (5) hand-operated dredges used by on-foot shellfishers along the Mediterranean and South Atlantic coasts of Andalusia, targeting *D. trunculus*.

SSF vessels targeting clams generally operate in nearshore waters. Since the 1980s, the management of coastal fisheries in Spain has been decentralised [27], allowing autonomous communities ("*Comunidades Autónomas*", or AACC) full authority over regulatory and licensing frameworks. Fishing permits, designated fishing areas, quotas, allowable fishing days, and operational schedules are all part of these frameworks. However, despite the diverse

governance models and regulatory systems employed by each AACC, most clam fisheries have either collapsed or are currently experiencing significant declines [28–32]. Fisheries governance includes both official and informal regulations, institutions, and decision-making processes that delineate access to and exclude marine resources, thereby enabling stakeholders to influence their utilisation and management [33]. The distribution of commercial clam species is often patchy, with dense populations restricted to specific sites where environmental conditions are favourable. This has resulted in concentrated fishing efforts in relatively small areas. However, the natural biogeographical boundaries of clam populations frequently do not align with administrative borders. For instance, [34] identified three distinct populations of *D. trunculus*: one spanning the Catalan and Valencian autonomous communities, another along the Mediterranean coast of Andalusia, and a third along the Atlantic coast of Andalusia. This implies that different regulatory regimes and fishing pressures have historically affected a single Northwestern Mediterranean population across its range. To date, research focusing on SSF targeting clams has primarily remained local, concentrating on individual AACCs in Catalonia, Valencian Community, and Andalusia [28,32,35–37]. However, no studies have yet evaluated these fisheries at a broader regional scale. The present study aims to fill this gap by providing the first regional-level analysis of the critical situation confronting commercial clam species along the Spanish coastline.

2. Material and Methods

2.1 Study area

Spain is divided into regions known as Autonomous Communities (AACC), each possessing its government and regulatory powers [38] These AACC run along the Mediterranean coast from north to south. They include Catalonia, the Valencian Community, the Balearic Islands, Murcia, and Andalusia (**Fig. 1**). This 2,200 km coastline is home to diverse ecosystems shaped by natural processes and human activities. It faces significant anthropogenic pressures, particularly due to high population density and seasonal tourism during the summer months [39]. Industrial centres, including Barcelona, Tarragona, Castellón, Valencia, Alicante, Cartagena, Almeria, and Málaga, contribute to localised pollution, whereas agricultural runoff has a more diffuse but comparatively limited impact [40] .

In contrast, the Atlantic coast of Andalusia represents a distinct ecological and socio-political region, extending approximately 300 km from the Strait of Gibraltar to the Portuguese border. This area is profoundly influenced by Atlantic oceanographic conditions, which include higher productivity, stronger tidal regimes, and seasonal nutrient inputs from significant rivers such as the Guadalquivir and Guadiana [41,42]. It also faces considerable human pressures, particularly from summer tourism and rapid coastal urbanisation, along with intensive agriculture in the lower Guadalquivir basin and around Doñana National Park [43]. Here, moderate to high environmental risks from pesticide contamination have been documented [44] Despite these pressures, the most pronounced declines in clam landings have been observed in the Northwestern Mediterranean Sea, which is therefore the primary focus of this study.

2.2 Data collection and analysis

This study combined official landing statistics and regulatory documentation to assess long-term trends and regional governance approaches in Spanish clam fisheries. Annual landings (1993-2024) for the three targeted species (*D. trunculus*, *C. gallina*, and *C. chione*) were obtained from the regional Fisheries Directorates of the AACC (Catalonia, the Valencian Community, the Balearic Islands, the Region of Murcia, and Andalusia). These datasets were supplemented with information from statistical yearbooks, grey literature, and peer-reviewed publications to ensure temporal continuity and reliability. To evaluate regional differences in management, a systematic legal and documentary review was conducted. For each AACC, all

available legal texts related to the management of target species were compiled and analysed, including regional decrees, ministerial orders, management plans, and administrative resolutions issued between the early 1980s and the 2020s.

Non-parametric statistical tests were conducted to examine temporal patterns and relationships in clam landings across various Spanish coastal regions from 1993 to 2024. Spearman's rank-order correlation coefficients were calculated to evaluate: (1) the relationship between total annual landings by species (*C. gallina*, *D. trunculus*, and *C. chione*) and the Autonomous Communities and Cities of Spain (AACC), including Catalonia, the Valencian Community, the Balearic Islands, Murcia, Mediterranean Andalusia (Alboran Sea), and Atlantic Andalusia (Gulf of Cadiz); and (2) the relationship among species' landings across three geographic areas: the Northwestern Mediterranean Sea, Mediterranean Andalusia, and Atlantic Andalusia. The aim of these analyses was to identify synchronies in temporal trends, regional disparities in exploitation patterns, and economic signals related to commercial demand. Correlations were deemed statistically significant at a 99.9% confidence level ($P < 0.001$).

To investigate structural changes in the temporal patterns of clam landings in Spanish coastal zones, we conducted a breakpoint analysis, employing the R package "*strucchange*" [45] as a statistical and methodological complement. This approach offers a robust framework for detecting discrete shifts in a univariate time series by segmenting the data into piecewise linear regressions, thereby facilitating the identification of years in which the dynamics of landings experienced significant changes. Specifically, we analysed the annual landing data for three species across three major fishing zones: the Northwestern Mediterranean Sea, Mediterranean Andalusia, and Atlantic Andalusia. The rationale for applying breakpoint analysis stems from its capacity to statistically identify deviations from a single linear trend, which may indicate ecological, environmental, or management-related shifts impacting fishery production. Methodologically, for each species–zone combination, we fitted a linear model represented by the equation $Tonnest_t = B_0 + B_1 * Year_t + e_t$. Tonnestt denotes the total annual landings (in metric tonnes) for each year (t), B_0 represents the intercept, B_1 indicates the slope that reflects the linear trend in landings over time, and e_t is the error term, which is assumed to be independently and identically distributed. The number of breakpoints is generally selected using information criteria, such as the Bayesian Information Criterion (BIC), which balances model fit with parsimony. This framework provides a statistical basis for interpreting changes in landings, thereby supporting the generation of hypotheses regarding underlying drivers, such as changes in fisheries management measures.

3. Results

3.1. Landings

The findings revealed strong and consistent positive Spearman correlations within the Northwestern Mediterranean, particularly concerning *C. gallina* (see **Table 1**). This species showed significant correlations across all four AACC (Catalonia, the Valencian Community, the Balearic Islands, and Murcia). Additionally, *D. trunculus* demonstrated a significant correlation between Catalonia and the Valencian Community. In contrast, the correlations between the Northwestern Mediterranean and the southern regions (Mediterranean Andalusia and Atlantic Andalusia) were weak, inconsistent, or non-existent, indicating that landings in these areas follow distinct trajectories. Consequently, landings were categorised and analysed by management area: (1) the Northwestern Mediterranean (comprising Catalonia, the Valencian Community, Murcia, and the Balearic Islands), (2) Mediterranean Andalusia, and (3) Atlantic Andalusia.

Table 1. Spearman rank-order correlation coefficients between annual landings of *Chamelea gallina*, *Donax trunculus*, and *Callista chione* across AACC (Catalonia, Balearic Islands, Comunitat Valenciana, Murcia, Andalusia Mediterranean coast and Andalusia Atlantic coast). ** indicates significance at P < 0.001.

	Balearic Is.	**C. Valenciana**	**Murcia**	**Andalusia Med.**	**Andalusia Atl.**
C. gallina					
Catalonia	0.745**	0.855**	0.630**	0.403	0.042
Balearic Is.		0.806**	0.728**	0.247	-0.185
C. Valenciana			0.693**	0.298	-0.752
Murcia				0.255	-0.459
Andalusia Med					-0.081
D. trunculus					
Catalonia	---	0.714**	---	0.362	-0.317
C. Valenciana	---		---	0.07	-0.455
Andalusia Med					0.345
C. chione					
Catalonia	---	---	---	0.461	---

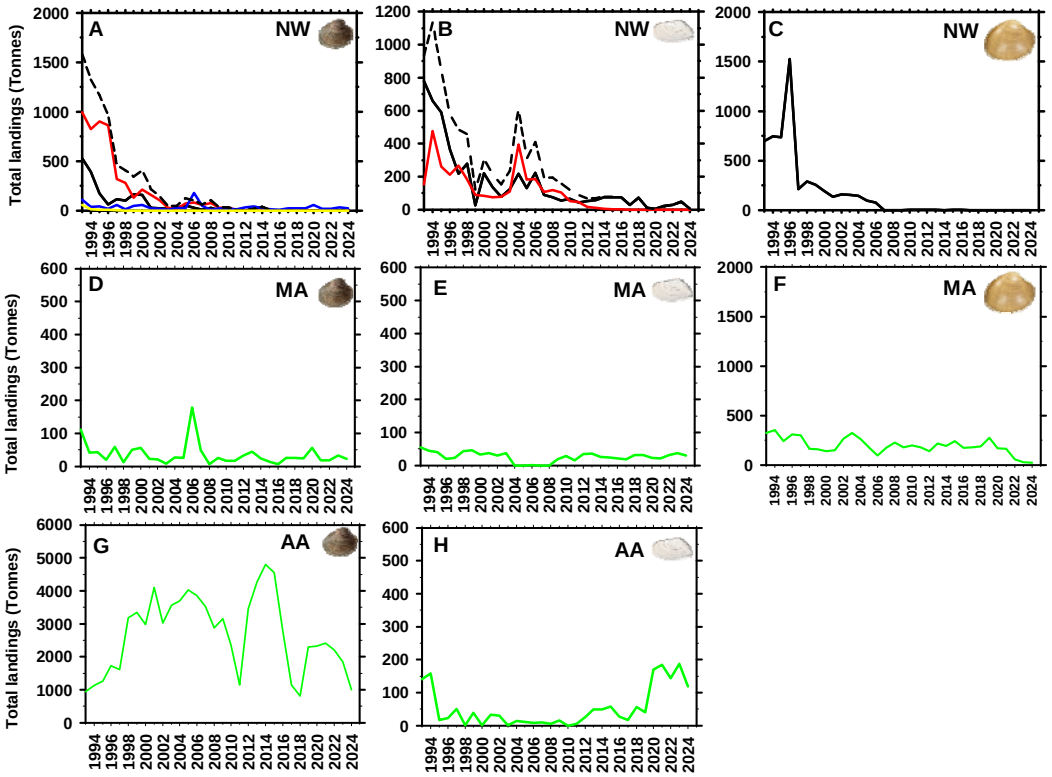

Figure 2. Annual landings (tonnes) of the three main commercial clam species: *(A, D, G) Chamelea gallina*; *(B, E, H) Donax trunculus*; and *(C, F) Callista chione*, across three geographic subregions: (A-C) Northwest Mediterranean (Catalonia, Valencian Community, Balearic Islands, and Murcia); (D-F) Mediterranean Andalusia (Alboran Sea); and (G-H) Atlantic Andalusia (Gulf of Cadiz). Coloured lines indicate landings by AACC: black for Catalonia, red for Valencian Community, blue for Balearic Islands,

yellow for Murcia, and green for Andalusia. The dashed black line in panels A and B represents the aggregated landings from all Northwestern Mediterranean AACC combined.

The Northwestern Mediterranean experienced a significant and simultaneous decline in *C. gallina* landings across all four AACCs during the late 1990s and early 2000s (**Fig. 2A**). The peak landing was 1,580 tonnes in 1995, followed by a dramatic collapse of over 80%, with landings falling to 46.8 tonnes by 2004. A slight recovery occurred in 2005 (126.3 tonnes), after which landings declined gradually, reaching zero by 2021. In recent years (2023-2024), catches have resumed exclusively in Catalonia but remain below 8 tonnes per year. In 1993, landings of *D. trunculus* reached their highest point at 1,137 tonnes (**Fig. 2B**). By 1999, they had dropped sharply to 115 tonnes in the same area. A modest recovery occurred in the early 2000s, with a secondary peak in 2004 at 612 tonnes, followed by a continuous decrease throughout the 2010s and minimal levels by the early 2020s. For *C. chione*, landings peaked in 1994 at 302 tonnes (**Fig. 2C**), but the fishery collapsed by 1998. Since the early 2000s, reported catches have remained close to zero, with no signs of recovery through 2024. Strong positive and significant correlations were detected among the three species in the Northwestern Mediterranean: *C. gallina* and *D. trunculus* ($r = 0.866$, $P < 0.001$), *C. gallina* and *C. chione* ($r = 0.847$, $P < 0.001$), and *D. trunculus* and *C. chione* ($r = 0.849$, $P < 0.001$).

On the Mediterranean coast of Andalusia, the landings of *C. gallina* exhibited a fluctuating pattern between 1993 and 2024 (**Fig. 2D**). Initially, catches declined from 111.2 tonnes in 1993 to just 8.8 tonnes in 2003 before rebounding sharply to reach 178 tonnes in 2006. However, this recovery was short-lived, as landings fell again to 7.4 tonnes in 2008. A moderate rebound then occurred from 2009 to 2015, with annual catches fluctuating between 14 and 44 tonnes. Following a further decline in 2016 (7.5 tonnes), landings increased gradually from 2017 to 2024, stabilising between 18 and 57 tonnes. This irregular trajectory may reflect unstable stock dynamics, shifts in fishing pressure, or regulatory changes. *D. trunculus* also exhibited a variable trend over the study period (**Fig. 2E**). Landings peaked in 1993 at 55 tonnes, then declined progressively to a minimum of 0.56 tonnes in 2005. A brief recovery occurred in 2006, but landings subsequently fell to zero in 2007. From 2008 onwards, catches stabilised at relatively low levels, fluctuating between 18 and 35 tonnes per year, with limited interannual variability. In contrast, landings of *C. chione* remained relatively stable along the Mediterranean coast of Andalusia from 1993 to 2021 (**Fig. 2F**), ranging from 130 to 351 tonnes per year, except for a slight dip in 2006 (93 tonnes). However, this trend has shifted recently: since 2022, reported catches have declined markedly, never exceeding 60 tonnes per year until 2024. No significant correlations were detected among the three species in the Mediterranean coast of Andalusia (*i.e.*, *C. gallina* and *D. trunculus* $r = 0.162$, $P = 0.374$; *C. gallina* and *C. chione* $r = -0.084$, $P = 0.645$; and *D. trunculus* and *C. chione* $r = 0.187$, $P = 0.645$).

On the Atlantic coast of Andalusia, the landings of *C. gallina* displayed the highest productivity of the three management areas (**Fig. 2G**), characterised by a pronounced boom-and-bust dynamic. After an increase from 1993 to 1998, catches remained relatively stable from 1998 to 2009, ranging between 2,800 and 4,100 tonnes per year. However, a sharp decline occurred in 2010, with landings dropping to 1,153 tonnes. This was followed by a strong recovery from 2012 to 2016, with annual catches fluctuating between 2,700 and 4,800 tonnes. In the years that followed, there were moderate changes: a drop in 2017-2018 (1,146 and 810 tonnes, respectively), a partial recovery in 2019-2022 (2,200 to 2,400 tonnes), and a drop in 2023 and 2024 (1,840 and 1,025 tonnes, respectively). This changing path shows that the fishery is very dynamic, probably because of changes in the environment and rules. In the same region, landings of *D. trunculus* showed marked interannual variability throughout the study period (**Fig. 2H**), allowing the identification of three distinct phases. The first phase (1993-2003) exhibited a pronounced decline, with annual catches decreasing from 157.5 tonnes in 1993 to only 0.6 tonnes in 2003. The second phase (2003–2011) was characterised by persistently low landings, generally below 15 tonnes per year. In contrast, the third phase (2011-2024) showed a progressive recovery despite interannual fluctuations, with catches ranging

from 60 to 110 tonnes annually and peaking at 186 tonnes in 2023. No significant correlations were detected between the landings of *D. trunculus* and *C. gallina* in this area (r = 0.307, P = 0.086, N = 32). Unlike the Mediterranean coast, *C. chione* is not commercially harvested in this geographical area.

The breakpoint analysis of clam landings across the three major Spanish fishing areas reveals distinct temporal patterns for each species, reflecting potential management interventions (**Fig. 3**). In the Northwestern Mediterranean (NW), *C. gallina* and *C. chione* showed a single early breakpoint around 1996, which was when landings dropped sharply. *D. trunculus*, on the other hand, showed a breakpoint in 1999, which meant that catches were lower than they had been in the past. These early declines likely reflect the combined effects of overexploitation and environmental constraints on recruitment. In the Alboran Sea (AM), breakpoints for *D. trunculus* occurred in 1997, 2003, and 2013, indicating episodic fluctuations in landings. *C. gallina* exhibited breakpoints in 2005 and 2009, while *C. chione* presented multiple breakpoints between 2001 and 2018, reflecting shifts in fishing intensity. In the Gulf of Cadiz (AA), *C. gallina* showed five breakpoints between 1997 and 2018, capturing a complex pattern of increasing, peaking, and declining landings, while *D. trunculus* exhibited breakpoints in 1996 and 2019.

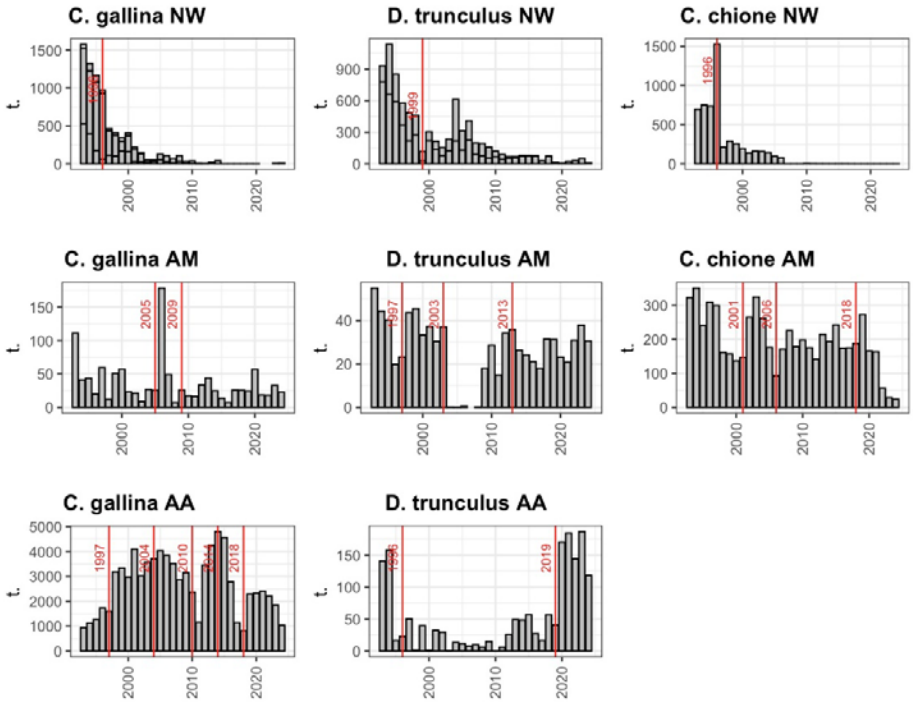

Figure 3. Breakpoints analysis to detect changes in the time series for each species. The red vertical line indicates the estimated point of change in the trend by specie and area.

3.2. Governance and management

The governance of small-scale fisheries (SSF), including clam fisheries, has been progressively decentralised in Spain since the early 1980s, following the approval of national decrees delegating competencies to regional governments (*e.g.*, Catalonia: RD 1646/1980; the Balearic Islands: RD 3540/1981; the Valencian Community: RD 3533/1981; Murcia: RD 4190/1982; and Andalusia*:* RD 3506/1983). As a result, each autonomous community has independently regulated clam fisheries within its territorial waters, resulting in a patchwork of

management approaches without interregional coordination (the significant differences in Minimum Legal Size (MLS) of *C. gallina* and *D. trunculus* between the AACC serve as an example (**Fig. 4**)). During the 1980s and 1990s, AACC legislation established basic appropriation rules, including restrictions on user access (*e.g.*, shellfish harvesting licences), gear specifications (*e.g.*, mesh sizes, number of dredges), MLS, mandatory screening of specimens at Fishermen's Guilds, and total allowable catch (TAC) limits. These measures were progressively reinforced in the 2000s in response to declining catches. The 2010s marked a turning point with the adoption of formal fishery-specific management plans, particularly to comply with EU requirements (Council Regulation (EC) 1967/2006 and Regulation (EU) No 1380/2013). Since the 2020s, these plans have continued to be updated. Nonetheless, despite divergent governance trajectories across regions and substantial regulatory effort, most fishing grounds have experienced pronounced declines or long-term closures, highlighting the persistent challenges of achieving sustainable and adaptive governance in clam fisheries (**Table 2; Fig. 5**).

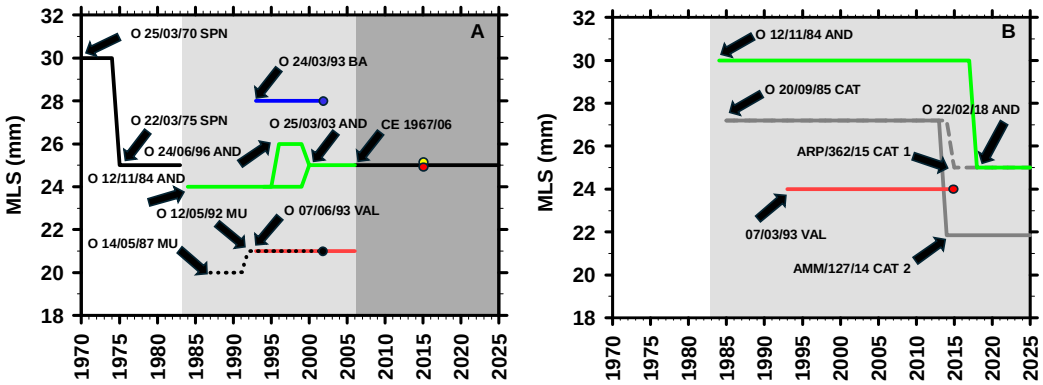

Figure 4. Evolution of the MLS in Spain. **(A)** *C. gallina*: The solid black line indicates the national MLS set by the central government between 1970 and 1983. After the decentralisation of fisheries competences (1980-1983), AACCs established their own MLS regulations. Red line: Valencian Community; dotted black line: Murcia; blue line: Balearic Islands; green line: Andalusia. From 2006 onwards, MLS was harmonised across Spain by the European regulation EC 1967/06. Catalonia is absent from the series because no MLS was defined until 2006. In the Valencian Community, Order 07/06/1993 did not specify an MLS but required sieving with a 19-mm circular mesh, which according to [37] corresponds to specimens larger than 21 mm. In the Balearic Islands, Order 24/02/1993 established a shell thickness >15 mm, equivalent to a total length of 28 mm (our data). In Andalusia, between 1996 and 2003, two different minimum sizes coexisted: 26 mm for hydraulic dredges and 24 mm for the remaining fishing gears. Dots indicate the year when fisheries were closed: blue for Balearic Islands, black for Murcia, red for Valencia, yellow for Catalonia. Letters inside the figure identify the regulation establishing each MLS (SPN, Spain; VAL, Valencian Community; BA, Balearic Islands; MU, Murcia; AND, Andalusia; CE, European Community). **(B)** *D. trunculus***:** Grey solid line shows Catalonia with hand-operated dredges; grey dashed line shows Catalonia with mechanised dredges; red line: Valencian Community; green line: Andalusia. The red dot marks the closure of the fishery in Valencia. In this case, Order 07/06/1993 required sieving with a 14 mm circular mesh, corresponding to specimens larger than 24 mm [37]. In Catalonia, Order AAM/127/2014 set a shell thickness of 7 mm, equivalent to a total length of 21.9 mm (our data).

Clam fisheries in Northwestern Mediterranean Sea

Clam fisheries in Catalonia historically relied on three main gears: winch-operated mechanised dredges (*C. gallina, D. trunculus, C. chione*), vessel-towed dredges (mainly *C. gallina*), and hand-operated dredges used by shore-based shellfishers (*D. trunculus*). This diversity created multiple user groups and access regimes, influenced both by ecological conditions and evolving institutional rules.

The first regulatory framework emerged in the mid-1980s, when Order 20/09/1985 established an MLS for *D. trunculus*, followed by Decree 9/1987, which created separate licensing schemes for mechanised dredges and hand-operated gears. During the late 1980s and 1990s, additional orders defined effort restrictions, sub-zoning of fishing grounds, and daily quotas, although enforcement was uneven and several areas remained poorly regulated. Conflicts between mechanised and hand dredgers, especially in the Ebro Delta, were frequent, while vessel-towed dredges targeting *C. gallina* operated with limited legal coverage.

In the 2000s, Catalonia attempted institutional consolidation. Order AAR/143/2007 unified technical standards for mechanised dredges, but compliance with gear specifications was poor and landings continued to decline. Reactive measures, including short-term closures (*e.g*., AAR/60/2008), were inconsistently applied and often reversed after disputes with other sectors.

The adoption of EU-driven management plans in the 2010s marked a significant shift. Orders ARP/362/2015 and ARP/122/2020 established gear-specific frameworks for mechanised dredges; Orders ARP/114/2018 and ARP/188/2020 established vessel-towed dredges; and Orders AAM/127/2014, ARP/256/2016, and ARP/182/2019 established hand-operated dredges. These plans introduced defined fishing grounds, technical standards, and participatory committees involving fishers, scientists, and administrators, though decision-making remained in administrative hands. By the early 2020s, nearly all mechanised dredging grounds had been closed, except for residual activity in the Ebro Delta and southern Barcelona. A partial reopening occurred in 2024, when *C. gallina* was again authorised for mechanised and towed dredges in specific grounds (**Supplementary Material with all the regulatory chronology**). Despite these advances, governance in Catalonia remains fragmented and inconsistently enforced, with limited integration of ecological knowledge and weak adaptive capacity. Current activity is residual, and clam fisheries continue to operate under precarious conditions.

Clam fisheries in the Valencian Community have historically relied on two distinct gears: mechanised dredges operated from vessels, targeting *C. gallina* and *D. trunculus*, and hand-operated dredges used by shore-based shellfishers for *D. trunculus*. These two modalities have long differed in their operational dynamics, access regimes, and levels of institutional oversight.

The first legal framework emerged during the late 1980s and 1990s. Order 15/09/1988 introduced a clam fishing licence, and Decree 67/1996 consolidated this system by formally distinguishing mechanised dredges from hand-operated dredges, thereby creating separate user groups. At the same time, the Resolution of 02/06/1993 classified production areas, and the Order of 07/06/1993 introduced technical limits on gear (maximum mouth widths of 75 cm for mechanised and 85 cm for hand-operated dredges), mesh sizes (19 mm for *C. gallina*, 14 mm for *D. trunculus*), and daily catch quotas. For hand-gatherers, permits were capped at 25 per guild. These rules clarified appropriation regimes but were poorly enforced and disconnected from ecological indicators, leaving the fishery highly vulnerable to overexploitation. Throughout the 2000s, no substantial new measures were introduced despite steep declines in landings, mirroring the collapse seen in Catalonia.

Stronger regulations only arrived in the 2010s. Decree 94/2013 updated the legal framework, followed by Decree 62/2016, which established a comprehensive management plan covering eligibility rules, fishing schedules, technical specifications, MLS, and total allowable catches (TACs). In parallel, closures were implemented: Resolution 09/08/2013 imposed indefinite bans on three fishing grounds: (Patacona-Cabanyal, Molinell-Deveses and Tavernes). With Resolution 03/06/2015, the closure was extended to the entire Valencian coast for mechanised dredges and to most areas for hand-operated dredges, resulting in a practical shutdown of the fishery. Resolution 18/05/2017 further extended the ban on hand-operated dredges targeting wedge clams to the remaining areas of the Valencian coast. The initial closed areas were intended to act as larval reserve zones, although no empirical evidence supported their ecological effectiveness. In practice, by 2015, the closure was almost complete, as

handgatherers operating outside the prohibited areas lacked authorised depuration facilities, resulting in irregular activity. Follow-up commissions involving guilds, scientists, and administrators were also created, representing a first step towards co-governance, although their role remained consultative and ultimate authority continued to reside with the administration (see **Supplementary Material with the full regulatory chronology**). Today, clam fisheries in the Valencian Community remain inactive, with indefinite closures in force and little evidence of recovery despite continued monitoring.

The clam fishery in the Balearic Islands was formally regulated in 1993, following the discovery of a productive ground for striped Venus clams (*C. gallina*) off Palma Bay. From the outset, only vessel-based mechanised dredges were permitted. Order 24/02/1993 established a mandatory licensing system, set daily catch limits based on crew size (15-20 kg for one fisher and 40-60 kg for three), and imposed a total allowable catch of 70 tonnes for the entire fleet. Each vessel was limited to two dredges, and working hours were initially capped at nine, later reduced to seven. Technical specifications for dredges and onboard mesh sizes were also defined. Furthermore, all catches were required to be inspected by local guilds before sale to ensure compliance with minimum size requirements.

Throughout the 1990s, regulations were frequently updated to refine appropriation rules. Annual adjustments included Order 31/10/1994 and a series of resolutions issued in 1995, 1996, 1997, and 1998, which modified schedules, quotas, and technical limits. Scientific monitoring complemented this adaptive approach but concerns about declining landings and early signs of resource depletion continued. In 2002, the regional government closed the Palma Bay fishery as a precaution. The closure was later extended without a plan for recovery, regular monitoring, or rules for reopening. A 2003 amendment to production zones was introduced but failed to establish specific provisions for clams. Consequently, the fishery has remained closed, lacking an effective framework for revival (see **Supplementary Material with all the regulatory chronology**). Despite the presence of relatively stringent appropriation rules and recurrent regulatory updates, the Balearic government's governance system remained highly centralised and rigid, devoid of participatory structures or adaptive capacity. This experience illustrates how a management approach focused on control and restriction, without meaningful stakeholder involvement, was insufficient in preventing collapse or supporting resilience in small-scale clam fisheries.

The case of Murcia is particularly noteworthy within the Spanish context, as regional authorities took over a clam fishery in the 1980s that was already facing a significant decline in landings. From the outset, management adopted a reactive and often improvised approach, frequently alternating between closures, adjustments to minimum size limits, and restrictions on fishing effort. This was done to balance the need for resource protection with the demands of the fishers.

The Resolution of 09/04/1984 introduced a minimum landing size (MLS) of 18 mm alongside a seasonal closure; however, this measure was swiftly repealed in 1985. A new regulatory cycle commenced with the Order of 09/04/1986, which reinstated the closure, increased the MLS to 20 mm, and imposed regulations regarding users, dredge specifications, and fishing schedules. In the subsequent years, frequent changes highlighted the absence of strategic planning: The Order of 09/09/1987 extended the fishing season, while the Order of 12/05/1988 curtailed it to June only, reduced fishing hours, and introduced daily total allowable catches (TACs). Following this, regulations alternated between extending and limiting fishing periods (e.g., Orders of 10/04/1990, 28/05/1991, and 12/06/1992), while progressively raising the MLS to 21 mm and restricting the number of dredges per vessel. Concurrently, the Resolution of 30/06/1995 closed one of the primary fishing grounds (Cabos Negrete-Palos), despite it having been repealed by a conflicting measure the year prior. In spite of this continuous fluctuation, landings continued to decline throughout the 1990s. Ultimately, the

Order of 16/06/2002 permanently closed all clam fishing grounds in Murcia, effectively shutting down the fishery. Scientific surveys conducted thereafter revealed no signs of recovery, and the closure remains in effect today (see **Supplementary Material for the complete regulatory chronology**). In summary, Murcia exemplifies a highly reactive governance system, characterised by frequent short-term regulatory modifications – encompassing MLS, fishing seasons, gear limits, and catch quotas – without a coherent long-term strategy. This unstable framework was ineffective in halting overexploitation or promoting adaptive management, ultimately resulting in the collapse of the fishery.

Clam Fisheries in Mediterranean and Atlantic Coast of Andalusia

Clam fisheries in Andalusia have developed under distinctly different conditions along the Mediterranean and Atlantic coasts. In the Mediterranean, the fishery primarily depends on vessel-based mechanised dredges operated by winches that target species such as *D. trunculus*, *C. gallina*, and *C. chione*. In contrast, in the Atlantic, *D. trunculus* is harvested with hand-operated dredges, while *C. gallina* is pursued using engine-powered towing and mechanised hydraulic dredges.

The initial rules for appropriation were established in the mid-1980s. Order 16/02/1984 set minimum legal sizes (MLS) of 24 mm for *C. gallina*, 30 mm for *D. trunculus*, and 60 mm for *C. chione*, as well as implementing seasonal closures. A shellfishing licence was introduced in Order 19/11/1984, while the fleet underwent its first census as mandated by Order 23/11/1986. Throughout the 1990s, geographic boundaries were defined (Orders 25/04/1993, 22/12/1998, 09/11/1999), and updates to the census were conducted (Order 24/10/1994). In the Atlantic, dredge fisheries gradually came under regulation: Order 24/06/1996 established technical standards for towed dredges, and Order 25/03/1999 governed hydraulic dredges, including stipulations on depth limits, catch quotas, and MLS (ranging from 24 to 26 mm). During the 2000s, the regulatory framework saw only minor updates, notably with Order 25/03/2003, which raised the MLS for *C. gallina* to 25 mm. A significant development was the creation of the Guadalquivir estuary reserve (Orders 16/06/2004 and 11/01/2005), which introduced zoning and distinct regulations for hydraulic dredges, towed dredges, and hand-gatherers.

The 2010s heralded a major shift in shellfishing regulations. Decree 387/2010 and Decree 99/2015 distinguished between on-foot and vessel-based shellfishing, establishing specific licensing schemes for each. In the Atlantic, following a collapse in landings, the Guadalquivir's *C. gallina* grounds faced a precautionary closure (Order 16/12/2010), along with subsequent temporary closures (Orders 30/11/2016 and 29/06/2017). The latter introduced a comprehensive management framework that incorporated quotas, satellite tracking, and monitoring. Concurrently, working hours and minimum landing sizes (MLS) were standardised through Orders 26/02/2013, 13/06/2013, 23/11/2017, and 22/02/2018. In the Mediterranean, management plans for specific types of gear were put into place (Order 24/03/2014; Order 27/12/2019). These plans included quotas, vessel monitoring, and punishment systems (**Supplementary Material with all the regulatory chronology**)

From 2020 onwards, Andalusia has developed one of the most advanced management systems in Spain. A dedicated order on 06/04/2020 established a management plan for *C. gallina* in the Atlantic, followed by annual fishing plans (Resolutions 22/07/2021; 04/11/2022; 13/07/2023) and precautionary closures when thresholds were exceeded (Resolutions 08/02/2021; 09/11/2022; 16/03/2023). For *D. trunculus*, Order 25/05/2020 regulated hand-operated dredges in the Atlantic, which was later consolidated with a management plan in Order 20/07/2023, also enforced with temporary closures (Resolution 05/10/2023). In the Mediterranean, adaptive plans were implemented, with closures triggered by scientific

assessments (Resolutions 05/12/2024 and 17/02/2025 for *D. trunculus*, and 18/10/2024, 27/02/2025, and 26/06/2025 for *C. gallina*) (see Supplementary Material for the complete regulatory chronology). Overall, Andalusia has progressively established a comprehensive, adaptive governance system, where scientific monitoring, satellite tracking, annual plans, and rapid closures are directly linked to stock assessments and management decisions. In contrast to other regions, Andalusia now serves as a benchmark for adaptive small-scale fishery (SSF) management in Spain.

Table 2. Governance and management of clam fisheries in Spanish AACC (1980s-2020s)**.** Summary of regulatory models, appropriation rules, enforcement, monitoring and assessment, fishers' participation and activity status across regions.

AACC	Period	Regulator model	Main appropriation rules	Enforcement	Monitoring & assessment	Fishers' participation	Status of activity
Catalonia	**1980s-1990s**	Top-down Weakly Regulated Reactive	Mostly limited to mechanized clam dredges. Limited to some and occasionally applied locally (*e.g.*, MLS, TAC, limits (depth and spatial), schedules, the number and engine power.	Low or very low	Very limited or absent	Fishers and fishers' guilds occasionally consulted but marginal.	All clam fisheries active.
	2000s	Top-down Weakly Regulated Reactive	Unification for all coast of mechanized clam dredges technical standards. Limited to some and occasionally applied locally (e.g., MLS, TAC, seasonal closures, depth limits, schedules, the number and engine power.	Low or very low	Limited to fishing grounds with sharp landings or absent	Fishers and fishers' guilds occasionally consulted but marginal.	All clam fisheries show declines. All fishing grounds active.
	2010s-2020s	Top-down with incipient co-governance (management committees)	Management Plans for each fishing gear. Many fishing grounds closure.	High	Intermittent	Higher participation (management committees).	All clam fisheries and fishing grounds closed except hand-operated fisheries in Ebro Delta. Residual activity of mechanized clam dredges in Ebro Delta and S. Barcelona. Towed dredges important activity in Ebro Delta since 2024, before fishery was closed.
Valencian Community	**1980s-2000s**	Top-down Weakly Regulated Reactive	Mostly limited to mechanized clam dredges. Limited (*e.g.*, MLS, TAC, limits (depth and spatial), schedules, the number and engine power.	Low or very low	Very limited or absent	Fishers and fishers' guilds occasionally consulted but marginal.	All clam fisheries active, but showed declines, particularly 2000s. All fishing grounds active.
	2010s-2020s	Top-down with incipient co-governance (management committees)	Management plan for mechanized clam dredges. Fishing grounds closure.	High	Regular after collapse	Fishers and fishers' guilds occasionally consulted but marginal.	All fisheries and fishing grounds closed.
Balearic Islands	**1990s-2000s**	Top-down Strictly regulated Reactive	MLS, TAC, limits (depth and spatial), schedules, technical characteristics of fishing gears and fishing vessels.	Low	Regular	Fishers and fishers' guilds occasionally consulted but marginal.	Clam fishery was active in 1990s, but showed declines, particularly 2000s and closure.

Murcia	**1980s-1990s**	Top-down Weakly regulated Very reactive	Chaotic with constant changes in seasonal fishing season, schedules, MLS, TAC etc.	low	Very limited or absent.	Fishers and fishers' guilds consulted.	Clam fishery showed declining trend.
	2000s	Top-down Weakly regulated Very reactive	Chaotic with constant changes in seasonal fishing season, schedules, MLS, TAC etc. Definitive closure.	low	Intermittent after the collapse.	Fishers and Fishers' guilds consulted.	Fishery and fishing ground closed
Andalusia	**1980s-1990s**	Top-down Weakly regulated	MLS, seasonal biological closures, geographical limits (spatial), schedules, fleet census.	low	Intermittent	Fishers and Fishers' guilds occasionally consulted but marginal.	All clam fisheries active.
	2000s	Top-down Weakly regulated	MLS, seasonal biological closures, geographical limits (spatial), schedules, fleet census, fishing reserves.	low	Intermittent	Fishers and Fishers' guilds occasionally consulted but marginal.	All clam fisheries active.
	2010s-2020s	Top-down Strong Regulated Adaptative management	Under continuous scientific advisor, very accurate (MLS, TACs, authorized and no authorized zones, schedules, reference biological points; fast response to oscillations in landings; biological closures etc.).	Very high	Continuous monitoring of all fishing grounds and target species.	Fishers and Fishers' guilds consulted.	All clam fisheries active.

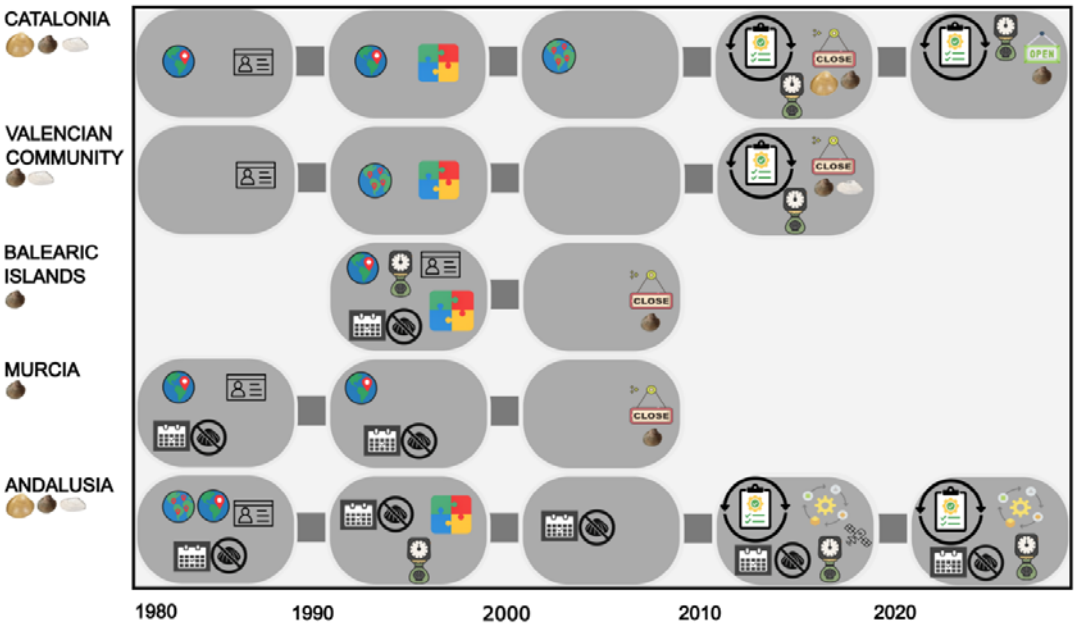

Figure 5. Chronological synthesis of the most relevant regulatory and management measures affecting clam fisheries in Spain by AACC, grouped by decade. The figure highlights the progressive shift from basic appropriation rules in the 1980s-2000s towards more formalized management plans, monitoring schemes, and adaptative management structures in the 2010s-2020s. Symbols denote the following categories: *clearly defined users* (specific shellfish harvesting licences, symbolising that access rights are restricted to licensed fishers), *local application of appropriation rules* (globe with a single point, symbolising rules applied only in specific fishing grounds), *regional application of appropriation rules* (globe with several points, symbolising rules applied at a regional scale across all fishing grounds, both vessel-based and on-foot fishers), *seasonal closures* (calendar and prohibition sign over clams, symbolising periods when harvesting is not allowed), *fishing grounds with defined limits* (interlocking puzzle pieces, symbolising clearly delineated spatial boundaries for clam harvesting areas), *satellite control of the fishing effort* (monitoring systems using satellites to track fishing activities and ensure compliance with management regulations), *Total Allowable Catch* (TAC, balance weighing a bag with clams, symbolising the regulatory limit on the maximum weight of clams that can be legally harvested per vessel and per day), *management plan* (checklist and gear within a cycle, symbolising predefined rules and procedures), *adaptive management* (gear with circular arrows and changing elements, symbolising flexibility and continuous adjustment of rules), *definitive closure of fisheries* ("closed" sign, symbolising the permanent closure of clam fishing grounds), and *fishery reopening* ("open" sign, symbolising the reopening of clam fishing grounds after a closure).

4. Discussion

Understanding the mechanisms that facilitate connectivity among fishing grounds is essential for developing sustainable management strategies for commercially exploited species [46]. The dispersal of clam pelagic larvae interconnects spatially discrete subpopulations, which in turn results in metapopulations [47]. Fisheries often target geographic areas that correspond to these subpopulations [48]. The duration of the pelagic larval stage determines how long the larvae remain in the plankton, during which time they may be transported by currents, winds, eddies, and other physical processes. This exposure influences dispersal distances and acts as a critical driver of genetic connectivity and population homogenisation in marine ecosystems [49,50]. Prevalent currents can transport pelagic larvae over considerable distances within a matter of weeks [50,51]. For the species discussed here, the pelagic larval stage lasts 15 and 30 days for *C. gallina* [52,53], approximately 60 days for *D. trunculus* [54] and between 32 and 39 days for *C. chione* [55]

Oceanographic processes like prevailing currents and hydrodynamic discontinuities along the Spanish coast affect how subpopulations are connected. These processes often act as natural barriers that structure marine populations [56] and affect how well spatial management measures work in

different areas. The Strait of Gibraltar and the Almeria-Oran Front (AOF) are among the most prominent of these discontinuities, representing consistent biogeographic and genetic breaks across multiple marine taxa [57]. The Strait of Gibraltar, a narrow ridge approximately 12.9 km wide and 284 m deep, separates the Mediterranean Sea from the Atlantic Ocean, with surface inflow of modified Atlantic water and deeper outflow of denser, saltier intermediate Mediterranean water [58,59]. The AOF, located off the southeast Iberian Peninsula, is a quasi-permanent boundary formed by the convergence of saline Mediterranean and less saline Atlantic waters. It separates the oligotrophic, saltier Balearic Sea (Northwestern Mediterranean) from the nutrient-rich Alboran Sea [60]. The strong correlations observed among clam landings within the Northwestern Mediterranean reflect the high degree of oceanographic connectivity in this subregion, where the absence of major hydrodynamic barriers promotes larval exchange between adjacent subpopulations. Conversely, the lack of correlation between the Northwestern Mediterranean, the Alboran Sea, and the Atlantic coast of Andalusia is consistent with genetic evidence suggesting that the AOF and the Strait of Gibraltar act as major barriers to connectivity for multiple marine taxa, including clams [34]

Spatial patterns of connectivity strongly intersect with differences in environmental productivity and habitat suitability, influencing the resilience of clam populations to exploitation [61]. In the Alboran Sea, the highest landings of *C. gallina* occurred in areas where upwelling processes were particularly intense and sediment properties provided favourable habitat conditions [32,62]. Sediment grain size also plays an essential role in determining the distribution of *D. trunculus* and *C. chione* [26,63]. Frequent interannual fluctuations in clam landings have been frequently reported throughout their distribution range [21,29,64,65] and are generally attributed to a combination of intense fishing pressure, distinctive life-history traits (*e.g*., rapid growth rates and short lifespans), periodic recruitment failures, and occasional mass mortalities [66,67]. In more productive regions, such as the Alboran Sea and the Atlantic coast of Andalusia [68–70], higher nutrient availability, favourable hydrographic conditions, and the presence of suitable sandy habitats provide a more resilient ecological setting for clam populations. Despite experiencing intense fishing pressure historically, target species in these areas have shown marked interannual fluctuations in landings, yet they often retain the capacity to recover following periods of decline. This pattern suggests that environmental productivity and habitat suitability can buffer the effects of exploitation, enabling the population to rebound when recruitment conditions are favourable. The different paths that subregions and even landings of the same species within the same subregion have taken can also be partly explained by ongoing differences in governance frameworks, regulatory consistency, fishing pressure, and the way that management measures fit with the biological limits of exploited stocks. While environmental productivity and habitat suitability (*e.g*., sediment type and hydrodynamics) provide the ecological baseline for population resilience, the capacity of the metapopulations to be exploited sustainably over time while retaining their ability to recover following declines is strongly influenced by regulatory design and coordination.

Differences in regulatory design and enforcement capacity have amplified the contrasting ecological trajectories observed across subregions. Where management has been largely reactive, intervening only after clear signs of a decline in landings, and has had a short-term vision, the recovery of clam stocks has often been limited or absent, even in areas with moderate environmental productivity (*e.g*., the Ebro Delta in Catalonia in Northwestern Mediterranean). This type of crisis-driven intervention resembles the "*event-based change*" described in organisational theory: short-term, reactive responses to unpredictable shocks that disrupt established routines [71]. Similar dynamics were described by [72] for the Yucatán fisheries, where governance was dominated by event-based, reactive strategies and struggled to achieve sustainability. While such responses may alleviate acute problems, they rarely address the structural vulnerabilities that predispose fisheries to collapse. In contrast, proactive approaches more closely align with the notion of "*time-paced evolution*", whereby adaptive adjustments are introduced continuously and deliberately over time to foster resilience rather than merely reacting to crises [73]. This concept strongly resonates with the principles of adaptive fisheries management, which aim to transition from reactive responses to structured systems of continuous learning [74–76]. Adaptive management emphasises the importance of learning from both successes and failures and of incorporating new information into decision -making processes, thereby reducing uncertainty and supporting resilience. It is particularly

advocated for fisheries with limited data and capacity [77,78]. In our case study of Andalusia, over the most robust example of this approach has been observed over the last two decades. The region has implemented annual effort limits, dynamic closures, and gear-specific regulations, complemented by constant resource assessments (*e.g.*, spatially detailed monitoring) and rigorous compliance controls (*e.g.*, inspection and enforcement of rules). The gradual integration of digital monitoring tools and decision support systems has further reinforced this adaptive framework, including electronic catch reporting, real-time quota tracking, and adaptive spatial management. These tools enhance transparency and responsiveness.

Beyond these institutional and technological advances, the spatial context of the fishery also plays a crucial role. The location of the main clam fishery within the Doñana National Park [79] the Marine Protected Area of the Guadalquivir estuary [80] and the Order of 16 June 2004, establishing a Fishing Reserve in the mouth of the Guadalquivir River, constitute a key element in terms of control and surveillance to prevent excessive fishing pressure. Being situated within this highly protected area implies the existence of stricter monitoring protocols, enhanced enforcement capacity, and increased institutional attention, which collectively reduce the likelihood of illegal, unreported and unregulated (IUU) fishing activities. Furthermore, this spatial setting creates a governance framework in which conservation objectives and fisheries management are more closely aligned, potentially leading to higher compliance rates and more effective effort limitation. This may therefore be a distinctive feature of these fisheries compared with the other stocks examined, as the regulatory and ecological constraints associated with the park's buffer zone provide an additional layer of protection beyond conventional governance frameworks.

Fisheries are frequently managed according to administrative or political jurisdictions rather than ecological scales [81,82]. This practice often generates spatial mismatches, particularly when jurisdictional boundaries are too narrow to capture the dynamics of exploited populations. This issue represents a major threat to the sustainability of the fishery [83]. Such misalignments can reduce productivity and promote the overexploitation of distinct subpopulations [84–86]. These discrepancies have been documented in many commercially exploited fish species, both pelagic and demersal, over the last two decades [83,87,88] but they are equally evident in sedentary or low-mobility invertebrates [89,90]. The stalked barnacle (*Pollicipes pollicipes*) fisheries in Spain, Portugal, and France are a good example of this. In these countries, administrative management plans break up populations that are biologically connected [90]. The sea urchin *(Paracentrotus lividus*) fishery in Galicia is another example. In these areas, local management units do not take into account genetic connectivity among subpopulations, which makes it more likely that local populations will run out of resources [91]. The same problem is evident in Spanish clam fisheries, where regional management by AACC does not align with the metapopulation structure of the target species in the Northwestern Mediterranean Sea. This situation reinforces stock vulnerability and limits the effectiveness of recovery measures.

Despite their considerable social and ecological importance, SSFs have historically received limited attention in the EU. For decades, they have been subject to weaker management, monitoring, and regulatory frameworks than their large-scale counterparts, largely due to their comparatively lower catches and economic value [15,92]. However, SSFs play a key role in generating employment and can represent a significant source of local economic activity. Beyond their economic contribution, SSFs strengthen people's attachment to their territory and contribute to social cohesion and stability in rural and peripheral communities [15]. A clear example of these factors can be seen in the clam fisheries in Spain, which have often been poorly regulated or virtually unmanaged for extended periods by the AACC, particularly in the Northwestern Mediterranean subregion. In Catalonia, the collapse of *C. chione* in the Maresme region after 2007 led to a *de facto* abandonment of the fishery, without any monitoring or recovery plans. Meanwhile in the Ebro Delta, clam dredging operated under minimal regulation until the 2010s. In the Valencian Community, much of the 1990s and 2000s resembled quasi-open-access regimes. The exploitation of *C. gallina* and *D. trunculus* occurred under nominal restrictions. This situation reflected both limited administrative capacity and the perception that these small-scale activities did not justify sustained investment in management. Regulations were generally restricted to a few appropriation rules (*e.g.*, users'

restrictions, MLS, seasonal closures, or gear restrictions), while systematic monitoring and scientific assessment of stocks were largely absent or inadequate. This scenario is particularly common in SSF, where costs and logistical challenges are higher [15,93]. Since the transfer of fisheries management responsibilities from the central government to the AACC in the 1980s, the governance of Spanish clam fisheries has consistently been based on a top-down model across all AACC.

In this traditional regulatory model, power is still mostly in the hands of government agencies, and decisions are often made without taking into account the real-life situations of fishing communities [94,95]. This mirrors a broader European trend whereby small-scale fisheries have traditionally been marginalised under policy frameworks primarily designed for industrial fleets, with little adaptation to the socio-ecological specificities of artisanal sectors [96]. Under this model, the involvement of fishers and Cofradias (fishing guilds) in governance was rarely considered beyond consultation processes, only gaining visibility once stocks had entered a state of critical decline. In Spain, fishing guilds are the main institutions organising and representing small-scale fishermen and shellfish harvesters, although their membership often extends to operators in more industrialised fleets. These guilds function as hybrid entities with both public and private dimensions [97], serving as advisory and collaborative counterparts to regional administrations in fisheries governance ([98] Spain). The exclusion of fishers and fishing guilds from governance participation has undoubtedly contributed to the recurrent depletion of fish stocks and ultimately to the collapse and closure of many clam fisheries, particularly in less productive areas such as the Northwestern Mediterranean Sea. Conventional top-down management approaches are increasingly viewed as inadequate, highlighting the need for governance models that integrate both ecological sustainability and social dimensions [99]. The [100] stressed the need for strengthening fishers' involvement in decision-making to improve institutional legitimacy and increase compliance with regulatory measures.

In recent years, European research has progressively paid greater attention to processes of decentralisation, the transfer of responsibilities, and the active involvement of fishermen in management frameworks [101–103]. Participatory co-governance models, also known as fisheries co-management, encompass a broad spectrum of institutional arrangements in which management responsibilities are shared between state administrations and resource users [104]. Co-management systems range from instrumental forms, where participation primarily facilitates the implementation of pre-defined rules, to empowering forms, where fishers genuinely contribute to the development of regulations [105,106]. Experience worldwide demonstrates that co-governance improves compliance, integrates fishers' ecological knowledge into decision-making, and strengthens the legitimacy and resilience of management systems [95]. The Asturian stalked barnacle fishery in Europe is a good example of this, with Territorial Use Rights for Fisheries (TURFs) managed by Cofradías showing that they can adapt and last for a long time [107]. Similar efforts in Chile and northwest Mexico show that co-management works best when there are laws that make it possible, rights are clearly defined, and institutions are stable [105,108]. These examples indicate that Spanish clam fisheries might gain from transitioning from mere symbolic consultation to authentic co-governance, wherein Cofradías and fishing communities assume a formal role in planning, oversight, and enforcement.

Of the AACCs analysed, Catalonia is the only region to have implemented a governance framework inspired by co-management, as outlined in Decree 118/2018 regarding the professional fisheries governance model. However, clam fisheries are not explicitly included within this framework. Instead, gear-specific monitoring committees—comprising mechanised dredges, hand-operated dredges, and tow dredges—were initially introduced as co-management bodies. In practice, these committees remain primarily consultative; while fishermen, scientists, and managers convene regularly, their conclusions are advisory only, with ultimate authority retained by the administration. This situation represents a limited form of participation rather than authentic co-management and fails to meet the criteria established in the literature [95,109,110]. The disparity between the narrative of co-management and its actual implementation highlights the enduring presence of top-down control and raises concerns regarding the timeliness and effectiveness of these mechanisms, particularly in light of the precarious state of clam resources. Furthermore, even if these committees were to operate as

genuine co-management entities, all decisions and management plans would still necessitate approval from the Directorate General for Maritime Fisheries and the European Commission, under the framework of the Common Fisheries Policy (CFP, Reg. (EU) No 1380/2013, which includes Article 18 regionalisation provisions). The CFP serves as the central mechanism of EU fisheries governance, providing a uniform regulatory framework for the fisheries of member states [111]. Consequently, the governance framework remains fundamentally top-down. This underscores an inherent conflict between scientific authority and democratic legitimacy, as fisheries management often relies on technocratic, expert-driven decision-making [112–114]. In the case of clam fisheries, the ongoing reliance on top-down decision-making allows for minimal adaptability in response to resource collapse. If co-management structures do not become genuinely binding and fail to incorporate fishers' knowledge into the decision-making process, management will persistently fall behind ecological decline. Consequently, an urgent transformation is essential to restore clam stocks and safeguard the livelihoods of coastal communities. As highlighted by [115], there is an increasing perception that top-down governance in European small-scale fisheries results in "*too little, too late*". This issue is particularly pressing in the Northwestern Mediterranean subregion, where delayed regulatory actions coincide with various stressors, including the accelerating effects of climate change, further jeopardising recovery prospects.

Overall, the case of Spanish clam fisheries highlights the critical interplay between ecological dynamics, regulatory design, and governance modes. In more productive areas, such as the Atlantic coast of Andalusia and parts of the Alboran Sea, clam populations have exhibited recurrent recovery after periods of decline. This resilience is supported by favourable environmental conditions and the gradual implementation of adaptive management measures. In contrast, less productive regions, particularly the Northwestern Mediterranean, have experienced recurrent collapses and long-term closures due to top-down governance, limited regulatory consistency, and the absence of supra-regional coordination. The main lesson is that sustaining small-scale clam fisheries requires shifting away from reactive management and fragmented jurisdictional strategies towards coordinated, supra-regional frameworks that are in line with biological population structures and integrate scientific assessments with fishers' ecological knowledge. This transformation is particularly urgent in the Northwestern Mediterranean, where overexploitation, low productivity, governance deficiencies, and climate change interact to create a highly complex problem. Nevertheless, ongoing attention is needed even in more productive regions to ensure that small-scale fisheries remain resilient and that traditional management practices do not erode long-term sustainability.

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7. Declaration of Interest statement:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

8. Data Availability:

Data will be made available on request.

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Supplementary Material: Key legislation on clam fisheries (1980s-2020s) by CCAA:

Catalonia

- **Order 20/09/1985**. Established minimum legal size (MLS) for *Donax trunculus* (27.2 mm length, 8.3 mm width).
- **Decree 9/1987**. Defined user groups authorised for mechanised clam dredges (winch-operated) and hand-operated dredges; created separate licensing frameworks.
- **Order 21/07/1987 (Roses)**. Introduced specific appropriation rules for Roses area (access, zoning, depth, quotas, vessel specifications).
- **Order 28/01/1988 (North Barcelona)**. Detailed regulations for fishing grounds in North Barcelona.
- **Orders 09/06/1993; 10/05/1994; 20/09/2000; AAM/89/2011.** Defining production areas for clams along the coast.
- **Order 13/06/1994 (Ebro Delta)**. Appropriation rules to resolve conflicts between mechanised dredges and hand gatherers.
- **Orders 01/07/1987; 26/10/1994; 31/07/1995; 03/10/1997; 10/08/1999; 18/10/1999**. Technical specifications for vessel-towed dredges (*Bolinus brandaris* as main target, up to 10% bycatches including clams).
- **Order 24/12/2001**. Increased allowable bycatches for vessel-towed dredges from 10% to 20%.
- **Order ARP/92/2002 (Roses)**. Temporary biological closure and restricted hours (repealed by **Order ARP/169/2003**).
- **Order AAR/143/2007**. Unified technical standards for vessels and mechanised clam dredges across Catalonia (mesh size, vessel specs).
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- **Order AAR/60/2008 (North Barcelona)**. Temporary closure and reduced daily fishing hours for mechanised dredges.
- **Orders AAM/127/2014; ARP/256/2016; ARP/182/2019**. Management plans for hand-operated dredges.
- **Orders ARP/362/2015; ARP/122/2020.** Management plans for mechanised clam dredges.
- **Orders ARP/114/2018; ARP/188/2020**. Management plans for vessel-towed dredges.

Valencian Community

- **Order 15/09/1988**. Introduced a clam fishing license; formally distinguished between vessel-based mechanised dredges and hand-operated dredges.
- **Resolution 02/06/1993**. Defining production areas for clams along the coast.
- **Order 07/06/1993**. Provided the initial legal framework for regional management; set limits on dredge mouth width (75 cm mechanised, 85 cm hand-operated), number of dredges per vessel (up to four), onboard sieving mesh sizes (19 mm for *Chamelea gallina*, 14 mm for *D. trunculus*), and daily catch limits; restricted the number of hand-gathering permits per fishermen's guild (cofradía) to 25.
- **Resolutions 20/01/1995;12/02/1996**; and **13/04/2007**. Establishing working hours for shellfishing activity along the Valencian coast.
- **Decree 67/1996**. Introduced an official clam fishing license, consolidating the distinction between mechanised dredges and hand-operated dredges, thereby creating separate user groups.
- **Decree 94/2013 (12 July)**. Updated the legal framework for clam fisheries; defined user eligibility, fishing schedules, technical gear specifications, minimum legal sizes, and daily TACs per vessel or shell fisher.
- **Resolution 09/08/2013**. Imposed indefinite closures for *C. gallina* and *D. trunculus* in three fishing grounds: Patagona-Cabanyal, Molinell-Devenes, and Tavernes.
- **Decree 62/2016 (20 May).** Established the first comprehensive clam fishery Management Plan; included rules for mechanised and hand-operated dredges, TACs, MLS, daily catch limits, and schedules.

- **Resolution 18/05/2017**. Extended the indefinite closure established in 2013 to cover the entire Valencian coast.

Balearic Islands

- **Order 24/02/1993** – Formally regulated the clam fishery; introduced a mandatory licensing system; set daily catch limits based on crew size (15-20 kg for one fisher; 40-60 kg for three); established a TAC of 70 tonnes; restricted vessels to two dredges; capped daily working hours at nine (later reduced to seven); and specified technical dredge requirements and onboard mesh sizes.
- **Order 31/10/1994** – Updated appropriation rules, including fishing schedules and effort controls.
- **Resolution 10/11/1995**. Annual update to appropriation rules.
- **Resolution 21/10/1996**. Annual update to appropriation rules.
- **Resolution 10/10/1997**. Annual update to appropriation rules.
- **Resolution 16/10/1998**. Annual update to appropriation rules.
- **Order 7/02/2001.** Establishing mollusc and other invertebrate production zones in the Balearic Islands.
- **Order 20/12/2002.** Regional government implemented precautionary closure of the Palma Bay clam fishery in response to declining landings.
- **Orders 07/02/2001; 28/03/2003**. Defining production areas for clams along the coast.
- **Resolution 28/08/2003.** Approving the call for aid for the temporary cessation of the wedge clam (*C. gallina*) fishery in Palma Bay.

Murcia

- **Resolution 09/04/1984**. Introduced minimum legal size (MLS) of 18 mm and temporary closure (April-July 1985).
- **Resolution 10/04/1985**. Lifted previous closure.
- **Order 09/04/1986**. Reinstated closure (April 1986-May 1987); raised MLS to 20 mm; regulated users, dredge specifications, and fishing schedules (07:00-13:00).
- **Order 09/09/1987**. Extended fishing period by one month.
- **Order 12/05/1988**. Shortened fishing season to June only; reduced fishing hours (07:00-11:00); imposed TACs of 20 kg per crew member/day.
- **Order 10/04/1990**. Expanded season (15 April-15 May); extended fishing hours.
- **Order 28/05/1991**. Lengthened fishing season by one additional month.
- **Order 12/06/1992**. Reduced fishing season (15 April-20 June); restricted hours (08:00-11:00); raised MLS to 21 mm; limited dredges per vessel; mandated sorting at guild markets.
- **Resolution 13/07/1994**. Repealed closure of Cabos Negrete-Palos before enforcement.
- **Resolution 30/06/1995**. Indefinitely closed Cabos Negrete-Palos fishing ground.
- **Order 16/06/2002**. Definitively closed all clam fishing grounds in Murcia; fishery permanently shut down.

Andalusia

- **Order 16/02/1984.** MLS: 24 mm (*C. gallina*), 30 mm (*D. trunculus*), 60 mm (*C. chione*); seasonal closures (6-8 months) (all Andalusia).
- **Order 19/11/1984.** Specific shell-fishing license introduced (all Andalusia).
- **Resolution 01/03/1985.** Adjusted closures; daily catch limits (150 kg/vessel) (Mediterranean, Algeciras-Punta Chullera).
- **Order 23/11/1986**. Census of the shellfishing fleet (all Andalusia).
- **Order 25/04/1993.** Delineation of clam fishing areas (all Andalusia).
- **Order 24/10/1994.** Update of shellfishing fleet census (all Andalusia).
- **Order 24/06/1996.** Regulated towed dredges for *C. gallina* (technical specs, 300 kg/day, MLS 24 mm) (Atlantic).
- **Order 22/12/1998.** Defined geographic boundaries of fishing grounds (all Andalusia).
- **Order 25/03/1999**. Regulated hydraulic dredges for *C. gallina* (MLS 26 mm, depth > 5 m, seasonal closure) (Atlantic).

- **Order 09/11/1999.** Updated delineation of clam fishing areas (all Andalusia).
- Order 28/01/2000. Regulation of striped venus clam (*C. gallina*) fishery in the Gulf of Cádiz (Atlantic).
- **Order 25/03/2003.** Raised MLS for *C. gallina* to 25 mm; minor closure updates (all Andalusia).
- **Order 16/06/2004**. Established Guadalquivir estuary reserve; zoning for dredges and hand gathering (Atlantic).
- **Order 11/01/2005.** Specific rules for subzones in the Guadalquivir reserve (Atlantic).
- **Resolution 02/05/2007**. List of vessels authorised in Guadalquivir Reserve Zones B and C (Atlantic).
- **Order 24/09/2008**. Regulation of professional on-foot shellfishing licenses (all Andalusia).
- **Order 23/09/2008.** Census of shellfishing vessels targeting bivalves and gastropods (all Andalusia).
- **Order 22/04/2010.** Modified on-foot shellfishing licensing (all Andalusia).
- **Decree 387/2010.** Distinguished on-foot vs vessel-based shellfishing; licensing schemes (all Andalusia).
- **Order 06/07/2010**. Modified Guadalquivir estuary reserve rules (Atlantic).
- **Order 16/12/2010.** Precautionary closure of Guadalquivir *C. gallina* fishery (Atlantic).
- **Order 01/04/2011**. Created shellfishing reserve in Huelva; modified on-foot shellfishing licenses (all Andalusia).
- **Order 24/06/2011.** Regulating shellfishing from vessels using hydraulic dredges in the Gulf of Cádiz and establishing a fishing effort adjustment plan for the fleet operating under this modality and fishing ground.
- **Order 28/09/2011.** Regulated vessel-based shellfishing with towed dredges in the Gulf of Cádiz.
- **Decree 64/2012.** Regulated working days, hours and vessel monitoring (all Andalusia).
- **Order 26/02/2013.** Standardised working hours across modalities (all Andalusia).
- **Order 13/06/2013.** Regulated fishing schedules (Atlantic).
- **Order 24/03/2014.** Management plan for mechanised dredges (Mediterranean).
- **Decree 99/2015.** Reinforced separation on-foot/vessel-based; licensing (all Andalusia).
- **Order 30/11/2016.** Temporary closure of *C. gallina* in Guadalquivir (Atlantic).
- **Order 29/06/2017.** Comprehensive regulatory framework for *C. gallina*; VMS, quotas, monitoring (Atlantic).
- **Order 23/11/2017.** Standardised working hours (all Andalusia).
- **Order 22/02/2018.** Reduced MLS for *D. trunculus* to 25 mm (all Andalusia).
- **Order 27/04/2018**. Adaptation of production zones of bivalves and invertebrates; controls (all Andalusia).
- **Resolution 24/09/2018.** Opening of *C. gallina* fishery in Gulf of Cádiz (Atlantic).
- **Resolution 01/10/2018.** Partial modification of Resolution 24/09/2018 (Atlantic).
- **Resolution 09/01/2019.** Sanitary classification of production zones (all Andalusia).
- **Resolution 30/01/2019.** Partial modification of Resolution 24/09/2018 (Atlantic).
- **Order 27/03/2019.** Modified hydraulic dredges regulation (Atlantic).
- **Resolution 04/04/2019.** Closure of *C. gallina* fishery in Gulf of Cádiz (Atlantic).
- **Resolution 21/06/2019.** Fishing plan for *C. gallina* 2019-2020 (Atlantic).
- **Order 27/12/2019.** Management plan for mechanised dredges (Mediterranean).
- **Resolution 11/03/2020.** Closure of *C. gallina* fishery (Atlantic).
- **Order 06/04/2020.** Dedicated management plan for *C. gallina* (Atlantic).
- **Resolution 03/04/2020.** Adjusted closure for *D. trunculus* (all Andalusia).
- **Resolution 25/06/2020.** Fishing plan for *C. gallina* 2020-2021 (Atlantic).
- **Resolution 22/07/2020.** Modified fishing plan for *C. gallina* 2020-2021 (Atlantic).
- **Resolution 15/09/2020**. Closure of *C. gallina* in production zone (Atlantic).
- **Order 25/05/2020**. Regulatory framework for on-foot *D. trunculus* (Atlantic).
- **Resolution 19/03/2021.** Sanitary classification of production zones (all Andalusia).
- **Order 28/01/2021**. Call for new on-foot shellfishing licences in Huelva and Cádiz.

- **Resolution 08/02/2021**. Temporary closure *C. gallina* (Atlantic).
- **Resolution 18/02/2021**. Closure of *C. gallina* fishery (Atlantic).
- **Resolution 23/06/2021.** Fishing plan for *C. gallina* 2021-2022 (Atlantic).
- **Resolution 22/02/2022.** Closure of *C. gallina* fishery (Atlantic).
- **Order 29/06/2022.** Modified Guadalquivir reserve rules (Atlantic).
- **Resolution 28/06/2022.** Fishing plan for *C. gallina* 2022-2023 (Atlantic).
- **Resolution 16/03/2023.** Temporary closure *C. gallina* (Atlantic).
- **Resolution 27/04/2023.** Call for fleet data submission (Atlantic).
- **Resolution 13/07/2023.** Fishing plan for *C. gallina* 2023–2024; extended 2020 plan (Atlantic).
- **Resolution 31/07/2023.** Opening *C. gallina* in zone AND-102 Barra del Terrón; modified technical measures (Atlantic).
- **Resolution 25/08/2023.** Opening *C. gallina* in zone AND-107 Doñana Norte; technical adjustments (Atlantic).