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A Systematic Classification of Adriatic Sea Fisheries Landings Trajectories

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Abstract

Fish populations are subject to multiple anthropogenic and environmental drivers that cause pronounced fluctuations in abundance. In certain cases, these fluctuations result in abrupt shifts that can disrupt fisheries, alter marine ecosystems, and affect ecosystem resilience and management. Therefore, distinguishing rapid changes from gradual trends is considered critical for understanding how exploited populations respond to cumulative pressures. While previous studies have documented abrupt changes at the community level in the Adriatic Sea, species-level evidence remains limited. In this study, we applied a systematic approach to classify Adriatic Sea fisheries landings (1970–2020). Time-series were categorized into four trajectory types: stable, linear, quadratic, and abrupt. Abrupt trajectories dominated the dataset, occurring in 11 taxa, while linear, quadratic, and stable dynamics were also observed, revealing pronounced heterogeneity in species-specific responses. Among taxa with abrupt trajectories, eight exhibited a single breakpoint, whereas three taxa showed two breakpoints, with the majority identified between the late 1980s and late 1990s. Characterizing these abrupt changes at taxa level provides critical insights into the resilience of exploited species and supports the development of flexible and adaptive fisheries management in the Adriatic Sea.

Keywords: abrupt shift; landing dynamics; Adriatic Sea; fisheries

1. Introduction

The interaction of multiple external drivers has induced substantial changes in the population size of many fish species in the Adriatic Sea, resulting in marked increases and declines across taxa [1,2]. Current Mediterranean fisheries management frameworks primarily address these pressures through technical measures, including the regulation of fishing effort, minimum landing sizes, and spatial or temporal restrictions on fishing activities [3]. However, evidence from a wide range of ecosystems indicates that changes in external drivers do not always lead to proportional or linear ecological responses [4–6]. Under certain conditions, marine ecosystems may depart from equilibrium and follow discontinuous trajectories, commonly referred to as abrupt shifts. Such shifts may arise from gradual changes of external drivers, rapid environmental changes, or synergistic interactions among multiple drivers [7]. Abrupt dynamics have been documented across ecosystems and organizational levels and can profoundly alter ecosystem structure, functioning, and feedback mechanisms that regulate marine communities [8,9].

The Adriatic Sea is widely recognised as one of the most heavily impacted regions of the Mediterranean, reflecting the long-term and combined influence of multiple anthropogenic pressures[10,11]. Climate change, fishing effort, land-based pollution and introduction of non-native species have been identified as major external drivers shaping Adriatic marine communities over recent decades[10–12]. Together, these pressures have led to pronounced changes in both population sizes and community structure across several fish taxa[13–16]. Previous analyses of Adriatic fisheries landings have consistently documented non-linear dynamics and regime-like changes in community composition, identifying the 1990s as a critical transitional period. This phase was characterised by a decline in large, long-lived predators such as sharks and rays and a concurrent increase in smaller, fast-growing demersal species, including red gurnard and red mullet[1,17]. These changes have been attributed primarily to increasing fishing pressure, with additional modulation by climate variability, particularly sea surface temperature (SST) and the Atlantic Multidecadal Oscillation (AMO),

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while the influence of the North Atlantic Oscillation (NAO) appears comparatively weaker[17].

Abrupt shifts have significant ecological and management implications, often reflected in fundamental changes in system structure, functioning, and resilience[7,18]. Once established, alternative states may persist even when external pressures are reduced, which limits the effectiveness of management measures[8]. In exploited marine systems, such shifts can alter species interactions, energy pathways, and the productivity of target stocks, ultimately affecting ecosystem services and fisheries productivity[19]. Therefore identifying the timing and nature of abrupt shifts is therefore essential for understanding how ecosystems respond to cumulative pressures and for supporting adaptive, ecosystem-based fisheries management[20].

Understanding the dynamics of abrupt changes provides important insight into the capacity of exploited populations to respond to environmental and anthropogenic pressure. Therefore, recognizing past abrupt shifts, as well as anticipating potential future transitions, is essential for improving adaptive fisheries management strategies, particularly in systems such as the Adriatic Sea, where multiple stressors act simultaneously[1,14,19].

2. Material and Methods

2.1. Data

Trajectory analyses were based on fisheries landings time series obtained from the General Fisheries Commission for the Mediterranean (GFCM). We analysed official landings data from Adriatic countries covering the period 1970–2020, routinely collected by GFCM and made publicly available through the FAO database. In the FAO reporting system, the Adriatic Sea corresponds to area 2.1 and includes the northern and central sub-basins, whereas the southern Adriatic, encompassing the Albanian coast and the southeastern Italian coast, is reported under area 2.2 as part of the Ionian Sea. To obtain a complete Adriatic dataset, Albanian landings data were extracted from area 2.2 and incorporated into the Adriatic time series. A similar correction was not possible for the southeastern Italian coast, as these data are aggregated with landings from the southern Italian coast within area 2.2 and cannot be separated.

Landings data from Adriatic countries showed substantial inconsistencies over time, reflecting differences in national reporting systems and changes in the Data Collection Framework (DCF). As a result, landings of several taxa were reported at different taxonomic levels across the time series. In some cases, species-level data were aggregated to higher taxonomic levels, or vice versa, preventing consistent species-level tracking over the full study period. To ensure temporal consistency, analyses were restricted to taxa with continuous records throughout the study period, excluding taxa with missing values likely caused by reporting artefacts rather than true absences.

Annual landings from all Adriatic countries were aggregated into a single cumulative time series for each taxon. After excluding taxa with long gaps in reporting, 27 taxa were retained for analysis: 11 at the species level, 7 at the genus level, 5 at the family level, and 4 comprising mixed-family groups (Table 1).

2.2. Statistical analyses

Our analyses of landing dynamics of the analysed taxa were performed using a systematic approach including a trajectory classification process and changepoint analyses[21]. As explained by the authors, a combination of several existing methods is employed to classify the time series in one of 4 trajectory types; no change, linear, quadratic and abrupt, following a three-step classification approach that includes; model selection, validation and reliability confirmation (see Pélissié et al. 2024**)**. Furthermore, the applied approach also confirms the presence the occurrence of potential abrupt shifts and the exact location of the breakpoints. The model that best described the trajectory of each time series was selected based on the lowest Akaike Information Criterion corrected for small sample size (AICc).

Based on the best model selected from the first step, the analyses proceeded in a second step of model validation, which includes 2 sub-steps. If step 1 selected an abrupt trajectory, the presence and timing of a breakpoint were subsequently validated using the asdetect package, an independent method for detecting abrupt shifts. This validation step reduced the risk of false classification as abrupt. A breakpoint was retained when asdetect package identified at least one shift within five time points of the breakpoint estimated in step 1. When no breakpoint was detected, or where an inconsistent breakpoint was identified, was detected, the trajectory corresponding to the second-lowest AICc was selected. If an abrupt shift was confirmed, a subsequent step searched for additional breakpoints to refine the description of the trajectory before and after the initial shift.

Table 1. Classification of Adriatic fisheries landings time series into a trajectory type based on model selection.

Nr.	Species/taxon	Trajectory classification
1	Atherinidae	Quadratic decrease
2	*Boops boops* (Linnaeus 1758)	Quadratic decrease
3	*Chamelea gallina* (Linnaeus 1758)	Quadratic stable
4	*Engraulis encrasicolus* (Linnaeus 1758)	Abrupt increase
5	Loliginidae, Ommastrephidae	Abrupt decrease
6	*Lophius* spp.	Quadratic stable
7	*Merluccius merluccius* (Linnaeus 1758)	Abrupt increase
8	*Micromesistius poutassou* (Risso 1827)	Quadratic decrease
9	Mugilidae	Quadratic stable
10	*Mullus* spp.	Linear increase
11	*Mustelus* spp.	Linear decrease
12	*Nephrops norvegicus* (Linnaeus 1758)	Quadratic stable
13	*Octopodidea* (superfamily)	No change
14	*Parapenaeus longirostris* (Lucas 1846)	Abrupt increase
15	Rajiformes	Abrupt decrease
16	*Sardina pilchardus* (Walbaum 1792)	No change
17	*Sardinella aurita* (Valenciennes 1847)	Abrupt decrease
18	*Scomber* spp.	Abrupt increase
19	Scophthalmidae	Abrupt decrease
20	Scorpaenidae	Abrupt decrease
21	Sepiidae, Sepiolidae	Linear decrease
22	*Solea solea* (Linnaeus 1758)	Quadratic stable
23	*Spicara* spp.	Abrupt decrease
24	*Squalus* spp.	Abrupt decrease
25	*Squilla mantis* (Linnaues 1758)	Linear increase
26	*Trachurus* spp.	Linear decrease
27	Triglidae	Linear increase

If step 1 selected another trajectory, or when the abrupt shift was not validated, model complexity was assessed by testing the significance of the highest-order term ($p < 0.05$). Linear and quadratic models were assessed using the slope and quadratic term, respectively. The final model was the one with the lowest AICc and the highest significant order.

The reliability of the classification obtained from the applied workflow was further investigated using complementary metrics, including weighted AIC (wAIC), Leave-One-Out cross-validation (LOO), and the Normalized Root Mean Square Error (NRMSE).

3. Results and Discussion

3.1. Trajectory classification

Using a systematic framework combining several existing methods to classify each time series into one of four trajectory types (no change, linear, quadratic, or abrupt) and to identify the timing of breakpoints when present. The trajectories exhibited variation among the taxa examined. Two taxa showed no long-term change (Octopodidea; *Sardina pilchardus*). Linear trajectories were observed for six taxa, including increasing trends (*Mullus* spp., *Squilla mantis*, Triglidae) and decreasing trends (*Mustelus* spp., Sepiidae–Sepiolidae, *Trachurus* spp.).

Table 2. Number and timing of breakpoints identified for taxa exhibiting abrupt landing trajectories.

Nr.	Species/taxon	Breakdate(s)
1	*Engraulis encrasicolus* (Linnaeus 1758)	1985, 1996
2	Loliginidae, Ommastrephidae	1994
3	*Merluccius merluccius* (Linnaeus 1758)	1986, 1998
4	*Parapenaeus longirostris* (Lucas 1846)	2012
5	Rajiformes	1990
6	*Sardinella aurita* (Valenciennes 1847)	1987
7	*Scomber* spp.	2015
8	Scophthalmidae	1997
9	Scorpaenidae	1998
10	*Spicara* spp.	1982, 1993
11	*Squalus* spp.	1997

A total of eight were found to exhibit quadratic trajectories (Atherinidae; *Boops boops*; *Micromesistius poutassou*; *Chamelea gallina*, *Lophius* spp., Mugilidae, *Nephrops norvegicus*, *Solea solea*).

The remaining taxa exhibited abrupt trajectories, including sharp increases (*Engraulis encrasicolus*, *Merluccius merluccius*, *Parapenaeus longirostris*, Scomber spp.) and sharp decreases (Loliginidae–Ommastrephidae, Rajiformes, *Sardinella aurita*, Scophthalmidae, Scorpaenidae, *Spicara* spp., *Squalus* spp.) (Table 1).

3.2. Temporal dynamics and abrupt changes

Among taxa exhibiting abrupt trajectories, either one or two breakpoints were detected. Single breakpoints were identified in eight taxa: Loliginidae–Ommastrephidae (1994), *Parapenaeus longirostris*, Rajiformes, *Sardinella aurita*, *Scomber* spp., Scophthalmidae, Scorpaenidae and *Squalus* spp. Two breakpoints were detected in the remaining three taxa: *Engraulis encrasicolus*, *Merluccius merluccius*, and *Spicara* spp. (Table 2). Breakpoints occurred predominantly between the late-1980s and late 1990s, with only a few detected in the 2010s.

Taxa exhibiting by two breakpoints manifested three successive phases, with abrupt transitions separating periods of contrasting landing levels. For *Engraulis encrasicolus* (Figure 1a), two breakpoints were identified in the mid-1980s and mid-1990s, respectively. These breakpoints delineated an initial period of relatively high landings from a pronounced decline, followed by a subsequent recovery.

Similarly, *Merluccius merluccius* exhibited two abrupt shifts (Figure 1c), with an increase around the mid-1980s and a decline towards the late 1990s, resulting in three distinct phases of landings dynamics. Furthermore, two breakpoints were also detected for *Spicara* spp. (Figure 1j), indicating a transition from moderate landings to a short period of higher values, followed by a sustained decline.

In cases where a single breakpoint was identified, taxa exhibited a pronounced transition from one persistent state to another. Loliginidae–Ommastrephidae (Figure 1b) and Rajiformes (Figure 1e) exhibited significant declines in landings following breakpoints in the early to mid-1990s. As illustrated in Figures 1h, 1i, and 1j, the Scophthalmidae, Scorpaenidae, and *Squalus* spp. exhibited sudden shifts in the late 1990s, resulting in lower landings in the subsequent period. A sharp decline was also observed for *Sardinella aurita* (Figure 1f) in the late 1980s, after which landings remained persistently low.

In contrast, abrupt increases were observed for *Parapenaeus longirostris* (Figure 1d) and *Scomber* spp. (Figure 1g). In both cases, landings remained relatively low and stable for most of the time series before increasing sharply after the identified breakpoint in the early to mid-2010s. This resulted in a new state characterized by higher mean landings. In all cases, post-breakpoint dynamics differed significantlly from pre-breakpoint conditions, indicating a shift in the underlying landings regime.

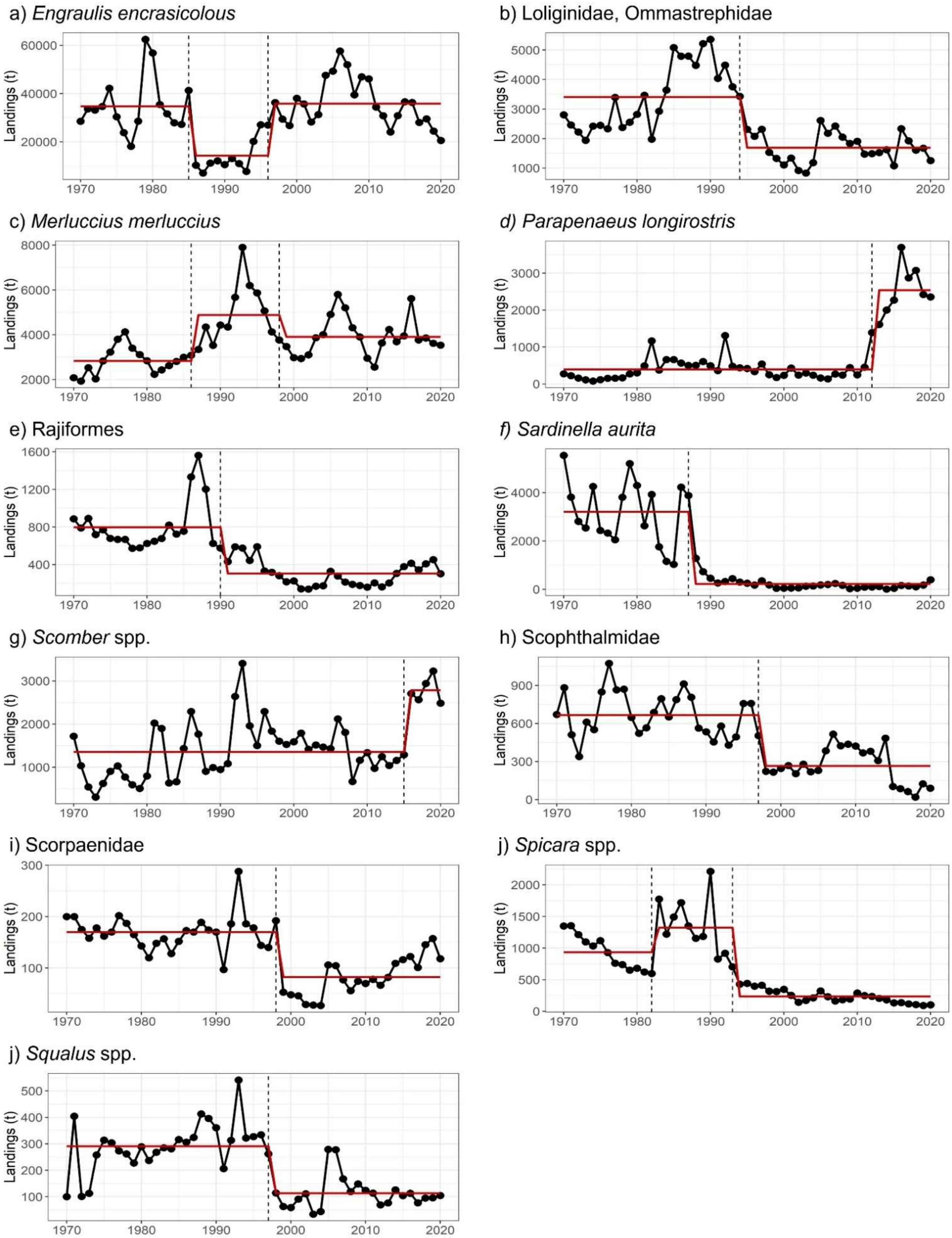

Figure 1. Temporal variation in landings (in tonnes) for taxa classified as abrupt. Black points and lines represent annual landings, solid red lines indicate mean landings within each segment. Vertical dashed lines denote the estimated breakpoints separating distinct temporal regimes.

Our analyses revealed the presence of distinct temporal trajectories in Adriatic Sea fisheries landings, highlighting pronounced heterogeneity in long-term population dynamics among taxa. Although abrupt trajectories dominated the overall landings community, linear, quadratic, and stable dynamics were also evident at the species and taxonomic-group level. For the majority of taxa exhibiting abrupt trajectories (9/11), the timing of the detected shifts coincided with the transitional period previously identified for the Adriatic Sea, reinforcing the notion of a system-wide reorganization during the 1990s[17]. These abrupt changes were closely associated with variability in local and regional climatic indices, particularly SST and AMO, while the influence of the NAO appeared comparatively weaker (see Kamberi et al. 2025). Importantly, despite the dominance of an abrupt trajectory at the community level, this pattern was not uniformly reflected across all taxa, indicating that species responded differently to the same set of external drivers (Table 1).

The identification of contrasting trajectory types underscores the importance of analysing population dynamics across multiple levels of taxonomic organization[22]. While fish populations are integrated within complex food-web interactions that can propagate changes across the community, species-specific responses remain critical for understanding ecosystem change[23,24]. This is especially relevant in the context of contemporary fisheries management frameworks, which largely operates through stock-specific reference points. Even though many Adriatic stocks are exploited by mixed fisheries, management advice provided by the Scientific, Technical and Economic Committee for Fisheries (STECF) often recommends differentiated exploitation levels among species[2]. Our results suggest that such management frameworks would benefit from explicitly accounting for non-linear and abrupt population dynamics, as well as from integrating community-level signals with species-specific trajectories to better reflect the complexity of ecosystem responses to combined fishing pressure and climate variability.

4. Conclusions

A substantially different situation is observed in cases where a single breakpoint is identified as species move to another state characterized by different landing levels and further analyses are necessary to investigate if taxa have established a new regime and its interlinked drivers.

The present study demonstrates that fisheries landings in the Adriatic Sea are characterized by various taxon-specific responses, highlighting substantial heterogeneity in population dynamics across exploited species. Overall, abrupt trajectories were the most frequently observed pattern, suggesting that many taxa experienced rapid shifts in landing levels over the study period. Such abrupt dynamics are often considered particularly vulnerable, as they may reflect transitions toward alternative system states, as documented in other marine ecosystems[25–27].

In most cases (8 out of 11 taxa), landings trajectories were characterized by a single breakpoint, indicating a shift to a new level of exploitation or productivity. In contrast, a smaller number of taxa exhibited two breakpoints, where short-lived transitions to higher or lower states were followed by a return to initial levels. These patterns likely reflect transient fluctuations rather than the establishment of a new regime, suggesting a degree of resilience and recovery capacity in these populations[20].

By contrast, taxa characterized by a single breakpoint appear to have transitioned to sustained changes in landings. For these cases, further investigation is required to assess whether these changes represent regime shifts and to disentangle the relative roles of fishing pressure, climate change, and their interactions. Collectively, our findings underscore the importance of species-specific analyses for detecting early signals of abrupt change and for informing adaptive, flexible management approaches.

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