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Fish dispersal from a sabotage-mediated massive escape event

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ABSTRACT: Farm sabotage can cause massive fish escape events with significant ecological and socio-economic risks. This study examined the fate of Mediterranean seabass *Dicentrarchus labrax* escapees following a large-scale escape event caused by sabotage in the Western Mediterranean Sea. We monitored the escapee density and size structure over 3 mo after the escape at increasing distances from the escape point, up to 45 km away. Fish density adjacent to the escape location 5 d after the sabotage was, on average, 114 ± 44.7 (SE) fish per 100 m^2. Our analyses showed that fish density decreased by 17% for every km away from the location, dropping to 2 and 1% after 1 and 2 mo, respectively, following the escape event. As escapee density declined throughout time and space, the size distribution of seabass shifted towards larger sizes. The rapid decrease in fish densities highlights the need for contingency plans focusing on fishing efforts in the coastal areas near the escape location (<20 km) within the first 24 h. These results are paramount to mitigating the risks associated with escape events cost-effectively. We emphasise the importance of sabotage prevention measures, such as security systems that can quickly detect intruders and trigger an immediate response to deter them. Additionally, enforcing appropriate sanctions based on the severity of the damage caused could help to discourage future sabotage attempts.

KEY WORDS: Aquaculture · Mediterranean seabass · *Dicentrarchus labrax* · Coastal zone management · Marine policy

1. INTRODUCTION

Fish escapes are a significant problem for aquaculture in most farming regions (Soto et al. 2001, Naylor et al. 2005, Jensen et al. 2010, Atalah & Sánchez-Jerez 2020). Aside from causing considerable economic losses, they can have drastic ecological, genetic, pathogenic, and socio-economic consequences. Escaped fish can compete for resources with wild fish (Soto et al. 2001, Valero-Rodriguez et al. 2015), predate on wild assemblages (Arismendi et al. 2009, Sepúlveda et al. 2013), modify native habitats (Sala et al. 2011), and reduce local diversity (Crowl et al. 1992, Bolstad et al. 2017). Introducing escapees to wild populations increases the risk of genetic introgression, which can alter the genetic composition, negatively affect the fitness and adaptability, and reduce the survival of wild populations (Glover et al. 2010, Miralles et al. 2016, Bolstad et al. 2017). Fish escapes can also increase the risk of disease and parasite transmission to wild fish (Arechavala-Lopez et al. 2013, Madhun et al. 2015). There is growing evidence that these interactions threaten the sustainability of wild fisheries, local biodiversity, and ecosystem functioning, highlighting the importance of preventing fish escapes and finding practical solutions to mitigate their consequences.

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Large-scale escape events are often the result of operational accidents, equipment failure, predator attacks, and storms, which are becoming more frequent and intense due to climate change (Sánchez-Jerez et al. 2008, Jensen et al. 2010, Arechavala-Lopez et al. 2018). Sabotage, the deliberate destruction or damage of farms, although less common (Jensen et al. 2010, Jackson et al. 2015), is also a significant cause of fish escape that generates substantial economic losses in biomass and infrastructure repair. Farm sabotages have been fuelled by conflicts between the aquaculture industry and other coastal users because of competition over fishing grounds, potential ecological impacts of aquaculture, and aesthetic concerns (Schlag 2010, Galparsoro et al. 2020). It has been hypothesised that farm sabotage may be carried out by poachers, as they would benefit from selling illegally recaptured fish. Examples of farm sabotage exist in most farming regions and have affected a wide range of farmed species (Irish Times 1996, La Verdad 2014, Molinari 2020, Undercurrent News 2020). For example, ca. 12 500 coho salmon escaped from a Chilean fish farm after a cage net was allegedly sabotaged in 2022 (Fish Farming Expert 2022). Recurrent farm sabotage in the Spanish Mediterranean Sea has led to repetitive large-scale fish escapes with an economic impact of millions of euros (La Verdad 2014). Unlike escape events due to storms, sabotage-mediated massive escapes occur when the sea conditions are favourable for reaching aquaculture facilities (i.e. summer season). The latter may entail differences regarding post-escape survival and spread, since recreational and professional fishing can recapture escaped fish immediately after the sabotage. In contrast, fishing activities during sea storms are limited, preventing recapture in the first days/week after the escape event. Although farm sabotages are recurrent events with significant financial and socio-economic implications, no study has described nor quantified the spatio-temporal dispersion and persistence of resulting massive fish escapes.

Environmental interactions arising from a massive fish escape, such as sabotage-mediated events, depend fundamentally on the dispersal capacity, resilience, and fishing mortality of the escapees (Jensen et al. 2010, Arechavala-Lopez et al. 2011, 2012, Toledo-Guedes et al. 2014). Redirecting fishing efforts to recapturing escapees can be fundamental in optimising recapture success, and represents one of the few management actions to mitigate environmental and socio-economic risks (Toledo-Guedes et al. 2014, Izquierdo-Gomez & Sánchez-Jerez 2016, Izquierdo-Gomez et al. 2016). Quantitative information on spatio-temporal dispersal and survival of escapees can help develop cost-effective recapture actions, and help in understanding the extent of escape event impacts. Previous studies have documented rapid dispersal and high post-escape mortality, for example, by tagging experiments (Uglem et al. 2008, Arechavala-Lopez et al. 2011, 2018) or visual censuses conducted after an escape event caused by a storm (Toledo-Guedes et al. 2014). However, no quantitative studies have described post-escapee persistence after an escape event caused by sabotage. The lack of quantitative studies on post-escape persistence in the case of sabotage highlights the need for further research in this area to inform contingency plans and mitigate socio-environmental risks.

Between July 8 and 9, 2014, a seabass farm on the SE Spanish coast in the Western Mediterranean Sea (Fig. 1) suffered sabotage, which provided a unique opportunity to evaluate the spread potential of fish after a massive escape event. The news and communication with the farming company indicated that several cages were sabotaged. Hundreds of thousands of European seabass *Dicentrarchus labrax* with sizes between 10 and 20 cm escaped into adjacent habitats. Here we quantify the spatio-temporal patterns in the persistence and spread of escaped seabass, as well as changes in the size structure of these fish assemblages. Such knowledge provides crucial information on the spread potential and survival of fish after a massive escape event that is necessary to inform contingency plans to mitigate the ecological impacts of escaped fish. Finally, we suggest specific features of contingency plans, including recapture actions, to enhance their cost-effectiveness in mitigating the adverse effects of escape events. We also offer prevention and control measures through monitoring.

2. MATERIALS AND METHODS

2.1. Survey design

Surveys were conducted on 14 July 2014, 5 d after the escape event, and then in August 2014 and September 2014. Visual censuses of escaped European seabass were carried out in shallow coastal waters (1 to 5 m). European seabass can be found at depths of up to about 100 m, but they are more commonly found in shallow waters (densities <0.1 individual per 100 m^2; Jouvenel & Pollard 2001, Toledo-Guedes et al. 2009), where escapees tend to concentrate after an escape event (González-Lorenzo et al. 2005). Snorkel-based dive surveys determined fish density and size

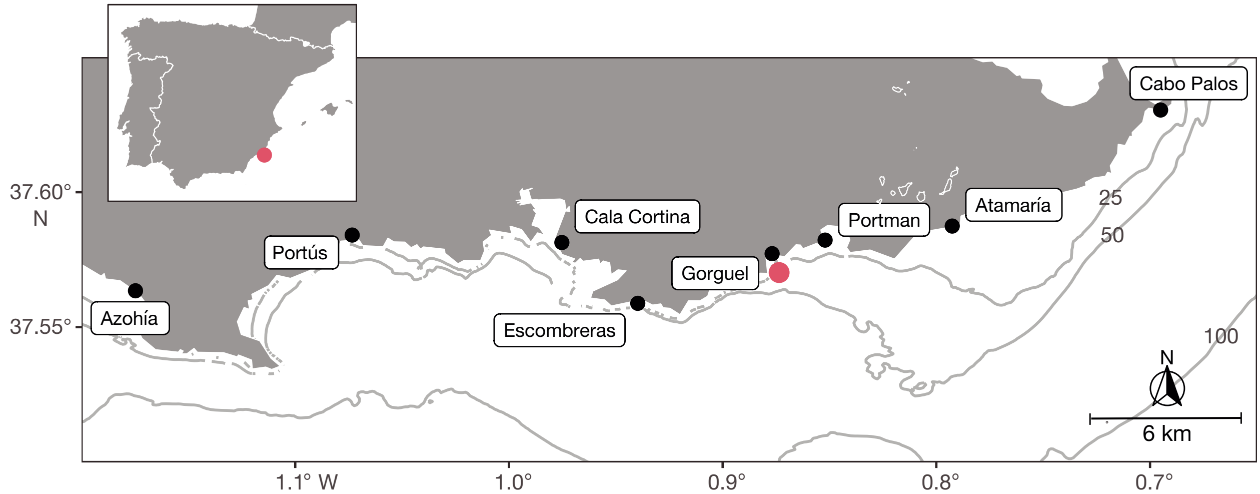

Fig. 1. Study area in the Western Mediterranean Sea, in relation to the Iberian Peninsula (inset) showing all sampling locations (●) and the sabotaged farm in El Gorguel from which European seabass *Dicentrarchus labrax* escaped (●). The 25, 50, and 100 m isobaths are shown based on data extracted from EMODnet (EMODnet Bathymetry Consortium 2020)

at 8 locations (Fig. 1). These were located at increasing distances in both the east and west directions from the escape point at the sabotaged farm. Four were located east of the escape point: El Gorguel (0.7 km), Portman (4.4 km), Atamaría (10.1 km), and Cabo de Palos (23.7 km); and 4 were located west of the escape point: Escombreras (6.4 km), Cala Cortina (12.6 km), El Portús (26.4 km), and La Azohía (45.3 km, Fig. 1). The distances to the farm were calculated following the coastline since this is the distance that escaped seabass are most likely to swim. At each location, 2 sites were surveyed, with 6 transects per site. Transects were visually sampled by snorkelers swimming 100 m in a straight line and observing the area within 2.5 m on either side (500 m^2). Snorkelers estimated the abundance and size of all seabass individuals encountered in each transect. Surveys were conducted by a 6 person snorkel team with at least 3 members sampling in all monthly surveys. Before sampling, pilot surveys were conducted to calibrate methods and ensure consistency between team members to allow direct comparability of the data.

2.2. Statistical analyses

Fish density data were standardised to fish density per 100 m^2, resulting in a continuous variable containing many zero values (73.6% of the 276 transects), and the non-zero data was highly overdispersed. As such, density data was analysed using generalised linear models fitted with Tweedie error distribution, which is more robust to overdispersed and zero-rich data than other distribution families (e.g. negative binomial or gamma). Zero inflation was tested with the 'testZeroInflation' function of the R package DHARMa (Hartig 2022), showing that the expected zero distribution was not significantly larger than that of the observed values. Thus, there was no need to incorporate zero inflation in the model. Therefore, we modelled density as a function of distance as a continuous covariate in km, month (July, August, and September), orientation (W and E) and the interaction (Distance × Month). To incorporate the dependency among observations of the same location and to quantify small spatial scale variability (hundreds of m), we used site nested in location as a random intercept. Models were selected by comparing the Akaike's information criterion (AIC) values of the full model and models with sequentially dropped non-significant terms. The final model with the lowest AIC value was validated by inspecting simulated residuals using the 'simulateResiduals' function in the package DHARMa. The contribution of fixed and random effects to the model's performance was calculated using marginal R^2 (accounting for fixed effects only) and conditional pseudo-R^2 (accounting for fixed and random effects, Nakagawa & Schielzeth 2013). Length frequencies were compared between months using a randomisation Kolmogorov-Smirnov test using the function 'clus.lf' in the fishmethods package (Nelson 2019). This test compares length frequency distributions for non-independent data derived from clustered sampling methods, such as transects. Seabass larger than 30 cm were excluded from the analyses because of the low probability that they originated from the escape event.

3. RESULTS

3.1. Spatio-temporal patterns of fish distribution

Escaped fish density significantly declined with increasing distance from the escape location in both orientations (east and west, Fig. 2, Table 1). In July, the average (±SE) density at the closest location from the escape (El Gorguel) was 114 ± 44.7 fish per 100 m^2, which declined to <1 fish per 100 m^2 at 10 km from the escape location. At 1 and 2 mo after the escape (i.e. in August and September), fish density had dropped to <1 fish per 100 m^2 at all locations (Figs. 2 & 3). Escapees were at very low densities or absent at distant locations (e.g. Cabo Palos) throughout the study (Fig. 3). The most parsimonious model, which included the effects of distance, month, and their interaction. confirmed these patterns. Orientation was not significant and was excluded from the model. The final model also included the random effect of site nested in location. The model predicted an overall average fish density (intercept of the model) of 43 individuals per 100 m^2 (95% CI: 10.49–178.96) at the escape location. The model indicated that fish density decreased by 17% for every km away from the escape location (Table 1, Fig. 3). Fish density was predicted to fall to 2 and 1% at 1 and 2 mo after the escape event, respectively. The expected density decay rate varied significantly with month (Distance × Month, $p < 0.05$, Table 1), being lower in August compared to July (8% decrease for every km away from the escape location). Additionally, there was relatively small site-to-site variability in fish density, evidenced by the slight variance for the random intercepts ($\tau_{00} = 0.60$, Table 1), the relatively small intraclass correlation coefficient (ICC = 0.19, Table 1) and the subtle difference between the conditional and marginal R^2 values (0.66 and 0.73, respectively, Table 1).

3.2. Fish size distribution

The average (±SD) fish size in July across all locations was 14.7 ± 2.4 cm, which increased to 24.5 ± 2.7 cm in August and 26.3 ±4.9 cm in September (Fig. 4). The randomisation Kolmogorov-Smirnov test showed significant differences in fish size frequency distribution in July compared to August and September ($p < 0.05$). Fig. 4 shows patterns in the size distribution of the escaped seabass over time and across locations. There was a clear shift in size distributions toward larger size classes during August and September when a few larger fish (>25 cm) were recorded primarily in locations adjacent to the escape location (Fig. 4). In July, thousands of fish between 10 and 30 cm were observed around the escape location immediately after the escape event.

4. DISCUSSION

Here we provide the first quantitative evaluation of the dispersal of escaped farmed fish from a sabotaged marine net-pen farm. The results showed that the fish dispersed rapidly in time and space from the escape area. This knowledge provides crucial information on the spread potential of fish after a massive escape event, and it is critical in informing contingency plans to mitigate potential socio-ecological and economic effects. The study results align with the expected dispersal patterns of massive fish escape events, with a significant decrease in fish density over time and distance from the escape location. Seabass density dropped by 2 orders of magnitude at the escape location after the first month and by 3 orders of magnitude after 2 mo. These findings are consistent with previous studies on the dispersal patterns of escaped

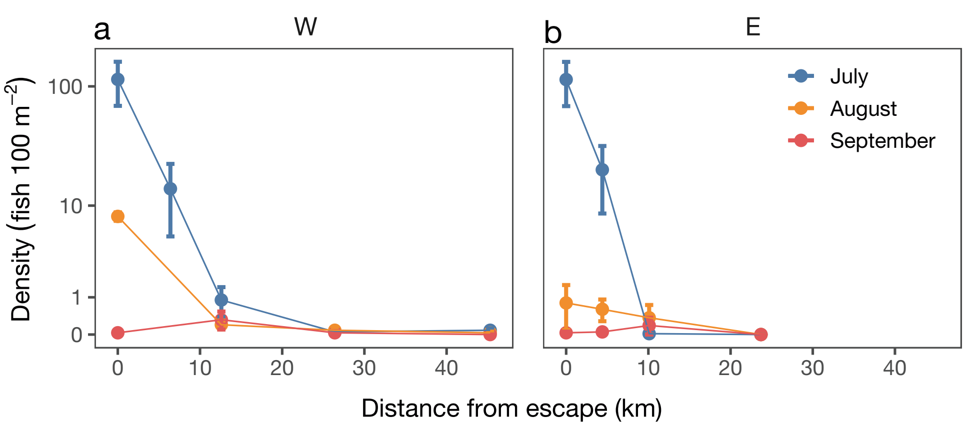

Fig. 2. Mean (±SE) fish density per 100 m^2 in relation to distance along the (a) west and (b) east coast from the escape location in El Gorguel where European seabass *Dicentrarchus labrax* escaped after a sabotage incident. Note the log scale on the *y*-axis

Table 1. Results of the generalised linear mixed model fitted with Tweedie errors and a log link testing the fixed effects of distance, months, and the random effect of site nested in location on escaped European seabass *Dicentrarchus labrax* density per 100 m^2. Estimates and associated 95% confidence intervals (CI) are exponentiated to represent the ratio of the expected values of the response variable (escapee density per 100 m^2) for a 1 unit increase in the predictor variables (distance and month), with July used as the baseline level. ICC: intraclass correlation coefficient; σ^2: residual variance; τ_{00}: variance of the random intercepts across sites nested in location

Predictors	Estimates	CI	p
(Intercept)	43.33	10.49–178.96	<0.001
Distance	0.83	0.79–0.87	<0.001
August	0.02	0.00–0.08	<0.001
September	0.01	0.00–0.04	<0.001
Distance × August	1.11	1.02–1.20	0.012
Distance × September	1.12	0.98–1.27	0.086
Random effects			
σ^2	2.61		
τ_{00}	0.60		
ICC	0.19		
$N_{location}$	8		
N_{site}	2		
Observations	276		
Marginal R^2 / conditional R^2	0.664 / 0.727		

farmed fish and restocking efforts for other species (Valencia et al. 2007, Toledo-Guedes et al. 2009, 2014, Solem et al. 2013, Skilbrei et al. 2015, Izquierdo-Gomez & Sánchez-Jerez 2016). Our results provide further evidence of this trend, and highlight the importance of monitoring and understanding the dispersal patterns of escaped farmed fish to inform effective mitigation strategies.

The strong spatio-temporal decay in the density of escaped farmed fish is underpinned by either fish mortality or migration outside the study area. Although our study does not allow for a distinction between these two processes, it is most likely that the described changes in fish density are a result of a combination of factors. However, we considered migration along the coastline less likely given the rare occurrence of escapees at distant sites (<1 fish per 100 m^2). It is possible that escapees migrated to deeper waters or outside the surveyed area. However, low densities were also recorded at depths of up to 24 m during SCUBA censuses as part of a parallel study (authors' unpubl. data). Although estimates of escapee survival rates are scarce, previous tagging and release studies have evidenced high mortality rates in natural habitats (Arechavala-Lopez et al. 2011, 2014). Post-escape stress and reduced food intake can increase mortality (Samaras et al. 2018), as farmed fish will likely be unsuccessful in foraging for live foods. Predation by large fish and birds immediately following an escape is another significant source of mortality (Handelsman et al. 2010). This is exacerbated by the poor ability of farmed fish to avoid predators in the wild and the small size of the fish that escaped (ca. 10 to 20 cm). Size-dependent natural mortality is a well-known driving factor in the success of restocking efforts (Olla et al. 1998).

Along with migration and natural mortality, fisheries can significantly contribute to the recovery of fish biomass following massive escapes with corresponding density reductions. For example, local professional fishers captured 22% of the 1.5 million seabreams and seabass that escaped from a farm in La Palma, Canary Islands (Toledo-Guedes et al. 2014). Similarly, professional fishers captured 64.7% of nearly 100 tons of seabream after a massive escape event near our study site (Izquierdo-Gomez & Sánchez-Jerez 2016). However, professional fishing played a marginal role in recapturing fish after the escape event at El Gorguel, since escaped fish were smaller than the minimum legal size

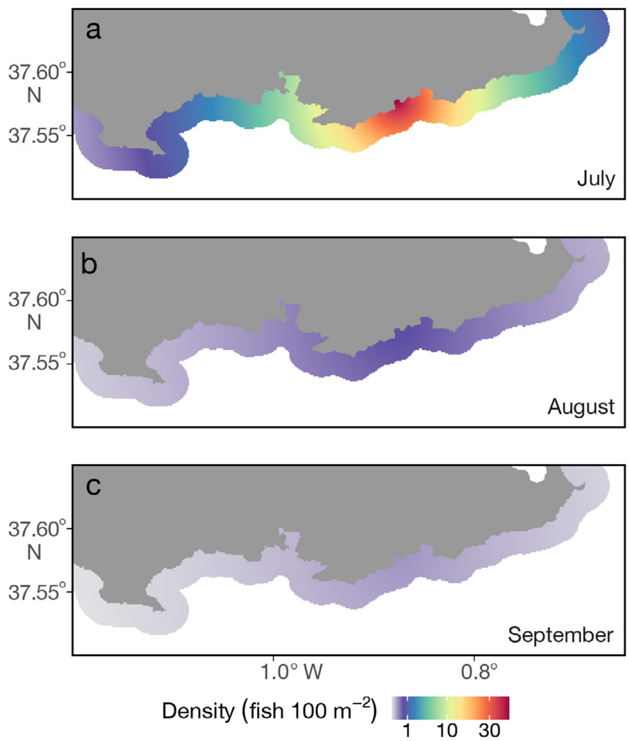

Fig. 3. Predicted escaped European seabass *Dicentrarchus labrax* density per 100 m^2 (log scale) by month across the study area as estimated by the final generalised mixed linear model with Tweedie errors to quantify dispersal from the sabotaged farm in El Gorguel. (a) July, (b) August, (c) September

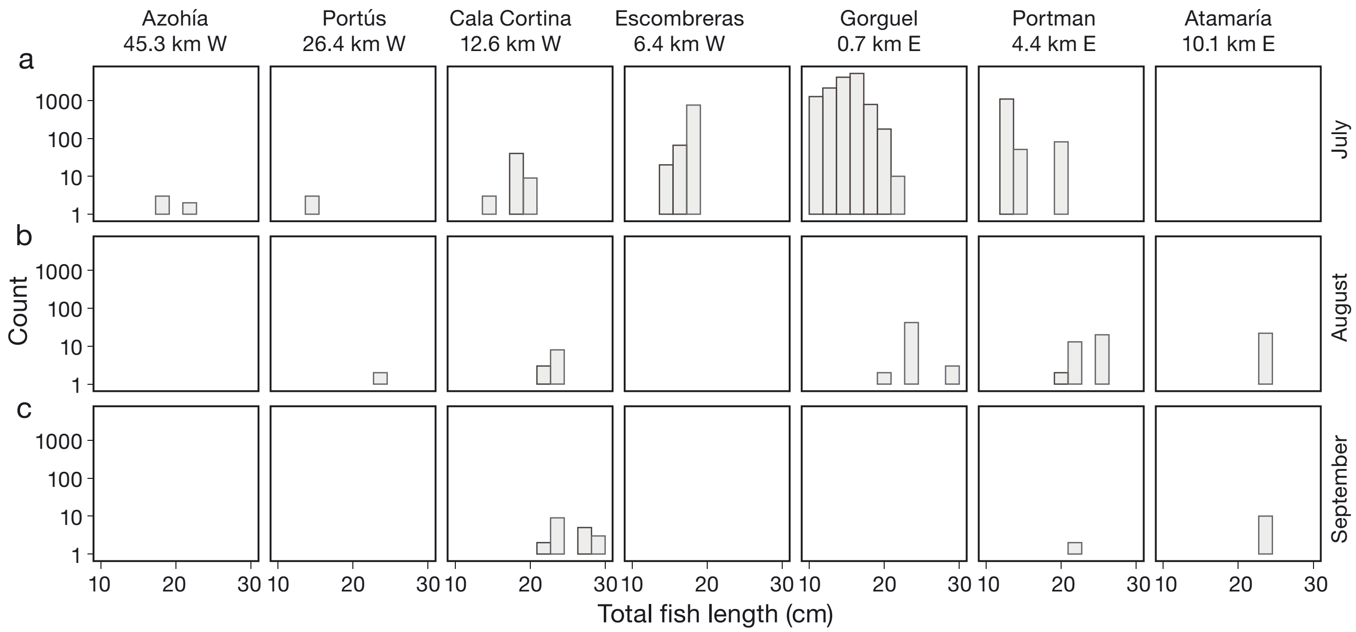

Fig. 4. Escaped European seabass *Dicentrarchus labrax* size frequency distribution by month and location ordered from west to east. The orientation and distance in km from the escape event are shown for each location. (a) July, (b) August, (c) September

(25 cm) and too small for the gear. This was confirmed by the absence of anomalies in seabass catches at the local fish market on subsequent days after the escape event. Although we did not monitor fishing effort, the number of recreational fishermen at proximate sites after the escape event was high (authors' pers. obs.). Therefore, we hypothesise that recreational fisheries significantly reduced escapee densities, including small-size classes, as legal-size controls are seldom enforced. The efficient role of fishing highlights the importance of relying on local fishermen to carry out the recapture actions to maximise rapidness and success. Fishermen own the logistics (e.g. fishing gear sets and boats) and know the coastline features. Such a co-management approach should be strongly coordinated between aquaculture facilities (escape alarms), fisheries (recapture actions), and administration (control of recapture plan effectiveness). Such management strategies could also benefit local communities when escaped fish have not been recently treated with therapeutics; otherwise, it could pose a public health risk (Figueroa-Muñoz et al. 2022). Implementing co-management strategies provides a synergistic approach that is beneficial for the aquaculture industry, local fisheries, administration, and, ultimately, the ecosystem.

As escapee density declined throughout time and space, the size distribution of seabass shifted towards larger sizes. The smallest classes (10 to 18 cm) were not recorded at 1 mo after the escape event, while large escapees were recorded 2 mo after. Although the dispersal of small individuals remains a possibility, the most plausible explanation is size-dependent natural mortality, with smaller individuals struggling to adapt and survive. Another possibility is that larger individuals may have been wild fish, as it is impossible to visually differentiate between wild seabass and escapees. In a study by Dempster et al. (2018), small escapees faced high mortality, hampering recapture efforts. The shift towards larger escapees holds significant implications for wild population conservation, as survival and establishment success are positively correlated with fish size (Olla et al. 1998, Handelsman et al. 2010). While all escapee sizes can impact ecosystems negatively, larger escapees pose heightened risks due to their increased reproductive and predatory potential (Brown et al. 2015). Farmed fish, with limited parental diversity, often have smaller populations and less genetic variation than their wild counterparts. Larger escapees can worsen genetic mixing, reducing diversity and increasing inbreeding, thereby endangering regional wild populations (Glover et al. 2017, Šegvić-Bubić et al. 2017, Alvanou et al. 2023). Additionally, the higher energetic demand of larger escapees could exacerbate several ecological impacts, such as predation and competition with wild species for trophic resources and habitat (reviewed by Arechavala-Lopez et al. 2018). It is crucial to consider these factors when developing management strategies, such as prioritising the recapture of larger individuals and adapting the features of the recapture gear (e.g. net mesh size), particularly when resources are limited.

Escape events are not considered in the Spanish aquaculture regulations, nor is their management, including monitoring programs. However, the European Union discourages member states from farming genetically modified organisms to mitigate the potential risk to wild populations from escapes (European Parliament, Council of the European Union 2014). A solid foundation of knowledge is paramount to prevent and/or mitigate potential adverse effects of escapees, especially in areas of ecological importance or conflict with other coastal users. Therefore, during the potential feralisation process of escapees, monitoring programs should assess genetic broodstock management, dispersion, their role as disease vectors, trophic interactions both as prey and predators, fishing mortality, and their role as a fishing resource. Marine protected areas (MPAs) are of particular concern regarding impacts, as these areas generally sustain endangered or vulnerable habitats and high species diversity. In our study area, the MPA Cabo de Palos e Islas Hormigas is about 20 km west of the sabotaged farm. No escapees were recorded at the closest site, and the model predicted low densities nearby. Thus, the spread risk within this MPA is negligible. However, to minimise risk, we recommend buffer zones around aquaculture areas. For instance, a 20 km buffer zone around fish farms could protect MPAs and other sensitive habitats.

The rapid expansion of finfish aquaculture within increasingly limited water space is likely to exacerbate already contentious social conflicts among the industry, fishermen, and other stakeholders. As a result, farm sabotages, such as the one described here, are becoming increasingly common across farming bioregions worldwide, including the Mediterranean. Three cages in the same facility were sabotaged 4 yr before the incident reported here, and thousands of seabass escaped. A few months later, a storm caused another massive escape event. Such incidents are likely to become more prevalent with the increasing frequency and magnitude of extreme weather events predicted under future climate scenarios (Sánchez-Jerez et al. 2022, Shukla et al. 2022). As such, our results have direct implications for guiding contingency plans to mitigate the impacts of escapees after massive escape events. We quantified for the first time the spatio-temporal patterns of a massive escape event caused by sabotage, showing that despite being a high-intensity event, escapees dispersed rapidly, displaying little persistence in adjacent areas over time. We strongly recommend the development of contingency plans under a co-management framework, with active roles for aquaculture facilities (informing about the escape event), local fishermen (adapting recapture actions), and administration (evaluating the effectiveness of the contingency plan). Ideally, aquaculture companies should inform the authorities and fishermen as quickly as possible about the escape event, species, and sizes of escapees. Recapture actions should be carried out 24 h after the escape and within <20 km from the event. Only fishermen have the potential to meet this requirement cost-effectively since they possess the know-how, boats, diverse gear, and solid knowledge of the coastal area. The recapture of larger escapees should be prioritised, and fishing gear should be specifically selected to meet this requirement. Rapid reporting and timely activation of these plans are essential for mitigating the negative impacts of escapes, including reducing the risks to wild fish populations, local biodiversity, and ecosystem functioning. From a prevention perspective, we recommend installing effective security systems on fish farms that can trigger rapid responses to dissuade intruders. We also recommend enforcing sanctions according to the damage incurred, to deter future sabotage attempts. By working closely with local fishermen and administration, aquaculture companies can help prevent sabotage-mediated escape events, maximise recapture rates and reduce the associated socio-environmental risks. This will ensure that the negative impacts are minimised and that the benefits of finfish aquaculture can be maximised while promoting sustainable development in harmony with other users of the coastal zone.

Data availability. Data and scripts used in the analyses are available at https://doi.org/10.5281/zenodo.7645374.

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