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Experiences from targeted removal of farmed Atlantic salmon from Norwegian rivers

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Abstract

Farmed salmon escaping from aquaculture and interbreeding with wild conspecifics pose a significant threat to the genetic integrity of natural salmon populations. Despite advancements in aquaculture security, escape incidents persist, prompting the need for effective mitigation strategies. This study summarizes experiences from efforts to remove escaped farmed salmon over a 12-year period in 63 western Norwegian rivers, using either (1) spearfishing during snorkelling by trained personnel or (2) traditional fishing methods employed by local groups. Recaptured farmed salmon ranged widely in size and included both spawners as well as immature fish, demonstrating that farmed fish entering rivers comprise fish of different ages and escape histories. Traditional fishing by locals recaptured the highest number of farmed fish, while removal during snorkelling in general captured larger and mature fish. On average, 53% of the farmed salmon observed during snorkelling were recaptured. This efficacy was influenced by the number of farmed fish present and the size of the farmed fish. In addition, efficacy increased over time, indicating that the removal team became more efficient. The study underscores that active removal, when executed judiciously, contributes to reducing the ecological risks associated with escaped farmed fish, complementing broader strategies for sustainable aquaculture.

Keywords: escaped farmed fish; aquaculture-environment interactions; salmon; genetic introgression; spearfishing

Introduction

The global aquaculture industry has grown tremendously during the last decades (FAO 2022). With an increased amount of fish farming comes an increased risk of collateral damage due to escaped farmed fish. Escaped fish may impact the environment by establishing feral populations (Naylor et al. 2001), interfering with wild conspecifics (Lura and Sægrov 1991, Einum and Fleming 1997), transmitting diseases to wild fish (Garseth et al. 2012), and causing genetic introgression with wild populations if they are able to successfully spawn in nature (Crozier 1993, Glover et al. 2012, Karlsson et al. 2016, Wringe et al. 2018). In fact, the effects of escaped farmed Atlantic salmon (*Salmo salar*) on their wild conspecifics, together with aquaculture-induced proliferation of salmon lice (*Lepeophtheirus salmonis*), have been assessed to be the highest man-made risks to wild Atlantic salmon populations in Norway (Forseth et al. 2017). Since the start of commercial aquaculture of Atlantic salmon in the 1970s, it has been estimated that 10s of millions of farmed salmon have escaped from aquaculture facilities (Glover et al. 2017) and many of the escapees have found their way into rivers. Interbreeding with wild salmon has caused genetic introgression in many salmon populations (Karlsson et al. 2016), which can lead to maladaptive behaviour and life history changes (Solberg et al. 2020, Bolstad et al. 2021, Besnier et al. 2022). While extensive technological and other measures have been taken to prevent fish from escaping, escape incidences regularly occur due to storm events, marine fish damaging nets, or human failure (Jensen et al. 2010, Føre and Thorvaldsen 2021). Consequently, with an increasing global demand for farmed fish, escapees are likely to continue to be an environmental concern in the future as the number of farms and farmed fish increase (Glover et al. 2020).

When escape events occur, the only viable mitigation method to minimize the environmental impact of the escapees is to attempt to recapture them. Deploying gillnets in the sea surrounding the sea cages after escape events has been a commonly attempted method for recapture. However, marine recapture attempts often have limited success (Dempster et al. 2018) as escaped farmed fish spread quickly away from the farm site (Skilbrei et al. 2010). In addition, gillnetting often results in unwanted by-catches of wild fish (Dempster et al. 2018). Other methods include stopping escaped farmed fish from entering rivers, by using fences or whole river fish traps where fish entering the rivers are screened and farmed fish may be removed (Madhun et al. 2023). However, such traps may require extensive infrastructure, are costly to operate, and cannot be installed in all types of rivers.

In cases where farmed fish have entered the rivers, they may be selectively removed either through traditional rod-fishing, netting, or more targeted methods such as spearfishing. Traditional fishing removal methods have the unwanted effect of wild fish bycatch. However, targeted removal by snorkelling requires visual assessment to locate and identify farmed fish and thus requires trained personnel. Visual underwater assessment of wild and farmed fish may be challenging, and some have questioned the validity of this method. However, Mahlum et al. (2019) found that snorkelers were able to accurately identify escaped farmed fish during snorkelling in a number of rivers in Norway, demonstrating that snorkelling can be a robust method to identify farmed fish given good conditions for underwater observations. This paves the way for targeted removal of farmed fish as a mitigation method in areas where escaped farmed fish are a management concern. Yet, little data exist to evaluate the efficiency of targeted removal efforts of farmed fish, wild fish bycatch rates (i.e. collateral damage), and what kind of fish that are most frequently caught by different removal methods. For example, the size and maturation status of fish may vary depending on when in the production cycle the fish escape and for how long they have been in the sea prior to ascending the rivers, which in turn may affect catchability among fishing methods.

Norway is the world's biggest producer of salmonids in aquaculture and in 2022 produced more than 828 000 tonnes of Atlantic salmon (Norwegian Directorate of Fisheries 2024a). Targeted efforts to recapture escaped farmed salmon from rivers in order to reduce genetic and ecological impacts of farmed salmon have been performed as a management practice in Norway for nearly 2 decades but have been more organized in the last 10 years. Removal efforts are frequently implemented after specific escape incidences, when aquaculture companies often are required by the government to organize removal efforts in nearby rivers. In 2015, a legislation was passed that required all aquaculture companies to establish an association (called OURO), for planning and funding measures to reduce the occurrence of escaped farmed fish in selected rivers based on previous data on occurrence of farmed fish (Glover et al. 2019), independently of known specific escape incidences. Furthermore, removal efforts have been more systematically implemented as part of monitoring activities in rivers funded by government agencies.

In the present study, we summarize data from removal efforts targeting escaped farmed salmonids in 63 rivers in western Norway during the period 2011–2022. The objective of the work is 2-fold; first, we analyse whether different removal methods catch farmed fish of different sizes and with different maturation statuses, as well as differences in collateral damage on wild fish. Second, we combine data from removal efforts with data from population surveys to analyse how efficient targeted removal efforts are with regards to reducing the number of farmed fish in rivers. The motivation of this study is to summarize the experience for the different approaches of removal of farmed salmon from rivers, and make recommendations for future removal efforts.

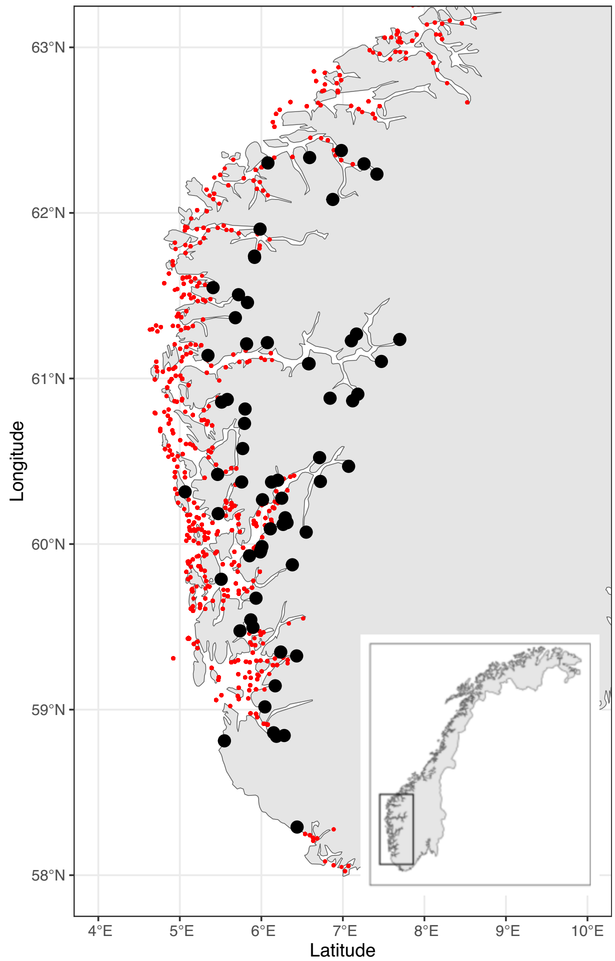

Figure 1. Map of western Norway with location of rivers with data from removal of farmed fish (•). Dots show commercial aquaculture locations with licence for production of salmonid fish (source: Norwegian Directorate of Fisheries 2024b).

Materials and methods

Data sources

The present study comprises data from 63 rivers on the southwest coast of Norway, an area with extensive aquaculture production (Fig. 1).

Data from removal of escaped farmed salmonids was assembled from various projects conducted in rivers on the west coast of Norway during 2011–2022. The data were obtained both from specific removal projects, such as efforts done in rivers immediately after escape incidences and organized removal activities from specific rivers (e.g. through the OURO programme), as well as various projects where farmed salmon were caught during other field activities in the rivers, such as population monitoring by drift diving. The data are mainly from two sources. The first is removal activities by spearfishing with rubber-thrusted spearguns (and occasionally targeted netting using seine nets, gill nets, dip nets, or captures with the hands) during snorkelling, performed by the Laboratory for Freshwater Ecology and Inland Fisheries, NORCE. In the following, this is referred to as *removal by snorkelling*. The second data source is local fishing groups using traditional rod-fishing and, in some cases, gill nets or manual sorting of fish caught in traps in fish ladders. Removal fishing by locals was in all cases performed in the autumn after the ordinary season for sport fishing in the rivers (if open for fishing) and organized by the landowners/river managers. In the following, removal based on local groups is referred to as *traditional fishing methods*. The dataset includes the majority, but not necessarily all, farmed fish recaptured by organized removal efforts in the relevant rivers, as some removal efforts also may have been performed by other institutions throughout the period.

Fish sampling

Data from individual fish were included for all individuals where there existed samples of scales and sufficient data on location/river and species. In addition to farmed

Atlantic salmon, the material includes unintentionally killed wild salmon and brown trout (*Salmo trutta*), as well as escaped farmed rainbow trout (*Oncorhynchus mykiss*). For most fish, there also existed data on fish size (length in cm and/or weight to nearest 0.1 kg), and for many, there also existed information on sex and reproductive status based on maturity levels of gonads (i.e. spawner or immature in the consecutive autumn). The fisherman usually also notes whether the fish is visually categorized as escaped farmed fish or wild fish. Wild salmon or brown trout caught during fishing are usually released without sampling, but wild fish that are fatally injured are euthanized and sampled. In addition, there are also incidents where the fishermen have incorrectly categorized wild fish as farmed fish, and therefore euthanized them erroneously.

The species and origin (wild, farmed, or hatchery) of all fish were independently evaluated based on scale readings (Lund and Hansen 1991, Fiske et al. 2005). The growth increment differences between wild and farmed salmon are usually distinct, but fish originating from supplementary hatchery releases as smolts can in some cases have growth patterns that are intermediate between wild and farmed fish, and thus be more difficult to distinguish. In Norway, most supplementary smolt releases are marked by removing the adipose fin, which is likely to be noticed by the fisherman and noted on the scale sample envelope. In cases, when the adipose fin was not removed and the scale reading was indecisive about hatchery/farmed salmon ($n = 29$) or hatchery/wild salmon ($n = 17$), the former was regarded as a farmed salmon and the latter as a wild salmon.

Removal efficiency during snorkelling

Data on efficiency of targeted removal efforts were obtained from rivers where removal activities were performed after the total number of farmed salmon in the rivers had been recorded in population surveys by drift diving. Drift diving was performed by teams of snorkelers drifting down the entire river accessible for salmon and recording the number of fish of different species and size categories (Skoglund et al. 2021). For salmon, three size categories are used: <3, 3−7, and >7 kg. Escaped farmed salmon are distinguished from wild salmon based on various morphological characters (Fiske et al. 2005, Jonsson and Jonsson 2006), such as deviating pigmentation patterns (Jørgensen et al. 2018) and fin erosion (Noble et al. 2007). These morphological differences are sufficient for experienced snorkelers to differentiate escaped farmed salmon from wild salmon with high accuracy given sufficient observation conditions (Mahlum et al. 2019). However, some misjudgement may occur as early escapees may have less conspicuous characters. In such cases, farmed salmon may be falsely categorized as wild fish. On some occasions, fish may also hide, avoid the drift divers, or stay in areas of the rivers unavailable for observation from the snorkelers. Thus, the number of farmed salmon counted by drift diving may on some occasions be an underestimate. The efficiency is here defined as the number of farmed fish *caught* compared to the number of farmed fish *observed* by drift diving. It should be noted that data include surveys where removal efforts were both the primary and secondary objectives (e.g. after population counting by drift diving), and thus that the effort levels may vary among the surveys.

The majority of fish caught by traditional fishing were caught in the lower parts of rivers or in estuaries. Because the total number of farmed fish in the rivers were most often unknown in cases where traditional fishing methods were used, and because we cannot determine the proportion of fish caught in estuaries that would eventually enter the rivers, removal efficacy could not be estimated for this method.

Data analysis

Reproductive status and size of escaped farmed salmon

To test whether the maturation status of escaped farmed salmon recaptured in the rivers was related to body size, we fitted binomial generalized linear mixed models (GLMMs). Reproductive status was modelled as a binary response variable (immature vs. mature), and either body length (in cm) or body weight (in kg) as fixed effects, and year and river as random effects.

To test for differences in size selectivity of the removal approaches (snorkelling vs. traditional fishing), linear mixed models (LMM) were fitted with length/weight as response variable, removal approach as fixed effect, and river and year as random effects. Differences in selectivity of removal approaches with regards to reproductive status was analysed by fitting a GLMM with reproductive status as a binary response variable, removal approach as a fixed effect, and year and river as random effects.

Efficacy of targeted removal efforts

The efficacy of targeted removal using spearguns and other methods is likely to vary among rivers due to various factors such as river size and the number and size of fish present, and may change over time due to increased experience among the snorkelers. To analyse this, we modelled the efficacy of targeted removal using a binomial GLMM. The number of farmed fish caught in relation to the total number observed in each river was used as a binomial response variable, and with average water discharge of the river, number of farmed fish, and number of wild fish (log transformed), as well as estimated mean body size of fish observed during snorkelling surveys, and year (numerical) as fixed effects, and river as a random effect. The mean body size of farmed fish during each of the surveys was estimated based on numbers of fish in each of the three size categories (<3, 3−7, and >7 kg), and assuming a mean size of 1.7, 4.4, and 9.4 kg for fish in each of the size categories, respectively, based on the size distribution from captured farmed fish.

All analyses were conducted using the software R (v 4.2.2; R Core Team 2022). LMM's and GLMM's were fitted using the *lme4* package (Bates et al. 2015), while predictions from the models were plotted using the *sjPlot* package (Lüdecke 2022). Model selection was performed by dropping single terms from the full model and testing for significance using likelihood ratio tests (LRT). The binomial GLMM's were evaluated for overdispersion using *DHARMa* package (Hartig 2022).

Results

The dataset included a total of 2568 Atlantic salmon caught in 63 rivers during the period 2011–2022. Based on scale analyses, 2445 of the Atlantic salmon were classified as farmed individuals, 90 as wild, while the remaining 33 were

Table 1. Summary of fish in the dataset caught during targeted removal by snorkelling and traditional fishing methods by local fishing groups by origin from scale analyses.

Approach	Method	Escaped farmed fish		Wild fish		Unclassified
		Salmon	Rainbow trout	Salmon	Sea trout	Salmon
Removal by snorkelling						
	Speargun	468	30	4	0	4
	Seine-net	49	0	3	0	1
	Gill-net	27	1	0	0	2
	Other	5	0	0	0	0
Traditional fishing methods						
	Rod	1718	39	78	2	22
	Gill-net	44	0	0	0	0
	Salmon ladder	14	0	2	0	0
	Unspecified	120	1	3	0	0
Total		2445	71	90	2	29

Unclassified means that origin was not possible to determine from scale analyses.

unclassifiable due to poor quality or missing scales. Of the 2445 farmed salmon, 549 were caught by targeted removal during snorkelling, while 1896 were caught using traditional methods (Table 1). In addition, 71 escaped farmed rainbow trout and 2 anadromous brown trout (wild) were caught. Farmed rainbow trout are not included in further analyses.

A total of 90 wild salmon and 2 wild sea trout were accidentally killed during removal efforts: 7 during removal by snorkelling and 85 by traditional fishing methods. Of the 92 wild fish killed, 73 (79%) were wild salmon (+1 sea trout) being misidentified as farmed salmon by the fishermen, 11 (12%) were euthanized due to injuries sustained during fishing, while the reason for the remaining 8 was not reported. The dataset also included 14 scale samples of farmed salmon that were released after capture as the anglers considered them wild or of uncertain origin. Most fish categorized as wild by the anglers are released without taking scale samples, and the number of farmed salmon misidentified as wild and released may therefore be higher.

Reproductive status and size of escaped farmed fish

Body length of farmed Atlantic salmon caught ranged from 32 to 115 cm (mean = 68.3, $SD = 13.5$, $N = 2320$; Fig. 2) and body mass ranged from 0.3 to 15.1 kg (mean = 3.6, $SD = 2.3$, $N = 2265$; Fig. 3). Reproductive status was reported for 830 fish, whereof 475 (57%) were mature and 355 (43%) were immature, and thus not ready to spawn the ensuing autumn. The likelihood of being mature increased significantly with increasing body length (LRT: $\chi = 147.4$, df = 1, $P < .001$; Figs 2): and mass (LRT: $\chi = 148.2$, df = 1, P < .001; Fig. 3). The mean body length for immature and mature fish was 63.4 cm ($SD = 12.4$, $N = 371$) and 80.6 cm ($SD = 12.1$, $N = 484$), respectively, and mean weight was 2.6 kg ($SD = 1.4$, $N = 363$) and 5.9 kg ($SD = 2.8$, $N = 450$), respectively.

Body size and reproductive status of farmed Atlantic salmon varied between capture methods, with removal by snorkelling catching fish of significantly larger body size than traditional methods, both with respect to length (LRT: $\chi =$ 91,7, df = 1, $P < .001$; Fig. 2) and weight (LRT: $\chi = 104.3$, df = 1, $P < .001$; Fig. 3). Removal by snorkelling also caught a significantly higher proportion of mature fish than traditional fishing methods (LRT: $\chi = 9.8$, df = 1, $P = .002$; Figs 2 and 3). There are data on reproductive status from 487 of the 549 fish caught by targeted removal during snorkelling, whereof 361 (74%) were mature. From the 1656 fish caught by traditional fishing methods by local groups, there exists data on reproductive status from 299, whereof 46 (15%) were mature.

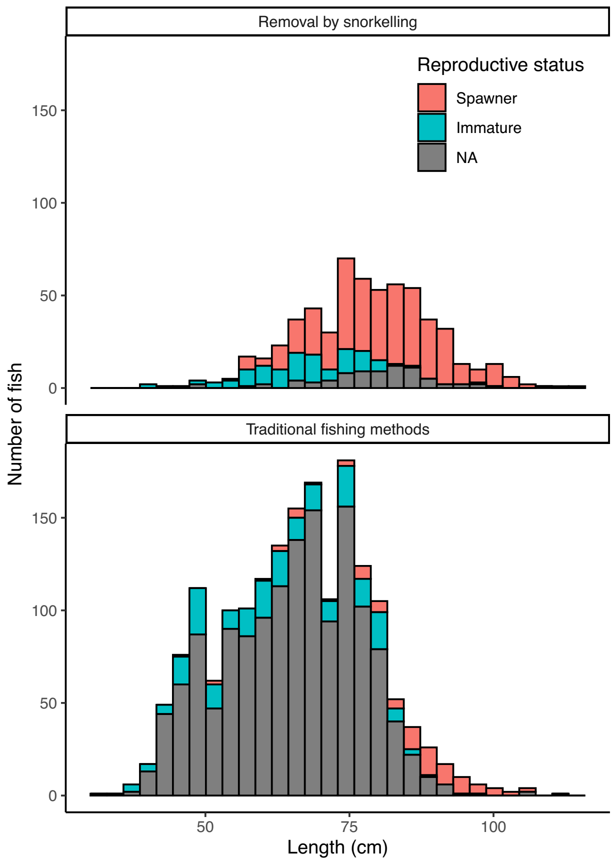

Figure 2. Body length and reproductive status of farmed Atlantic salmon caught by removal by snorkelling and traditional fishing methods.

Efficacy of targeted removal efforts

From the period 2011–2022, census data on population size of wild and farmed Atlantic salmon from drift diving existed for one year or more from 47 rivers (a total of 153 surveys/rivers/years) where removal of farmed salmon by

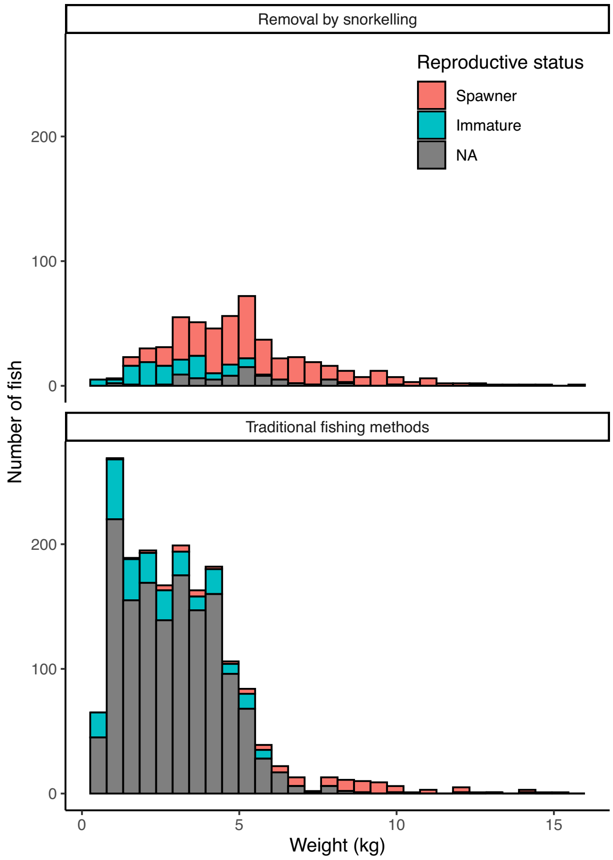

Figure 3. Body weight and reproductive status of farmed Atlantic salmon caught by removal by snorkelling (upper) and traditional fishing methods (lower).

snorkelling was simultaneously attempted. In total, 44 234 wild salmon and 1138 farmed salmon were recorded during the surveys. Of these, 440 (39%) of the farmed salmon were successfully removed.

The efficacy of removal varied considerably among surveys, rivers, and years. In 38 of the 153 surveys (25%), all of the farmed fish were successfully recaptured, whereas on 14 occasions none of the observed farmed fish were caught. The average removal efficacy across surveys was 53%.

Removal efficacy decreased with increasing numbers of farmed fish (LRT: $\chi = 19.1$, df = 1, $P < .001$) and increased with increasing fish size ($\chi = 52.2$, df = 1, $P < .001$) and through the period ($\chi = 10.6$, df = 1, $P = .001$), but was not affected by average water discharge ($\chi = 0.1$, df = 1, $P = .71$) or the number of wild salmon ($\chi = 0.3$, df = 1, $P = .53$) (Fig. 4).

Discussion

Reproductive status and size of escaped farmed fish

Farmed fish have been found to display a wide range of dispersal and migratory behaviour after escaping, with some seeking to rivers within a few days/weeks (Heggberget et al. 1993, Madhun et al. 2015, Quintela et al. 2016, 2023), while others may stay for one or more years in the sea before ascending rivers (Skilbrei et al. 2015, Aronsen et al. 2020). While smaller and immature fish typically tend to migrate to the ocean or disperse along the fjord and coast immediately after escaping (Skilbrei et al. 2010, Skilbrei et al. 2014), some also seek to rivers shortly after escaping. It is the mature escapees that ascend rivers and interbreed with wild conspecifics that pose the most serious ecological threat to salmon populations. However, the maturity status of farmed salmon recaptured in rivers is rarely reported in the literature. This limitation should be taken into account when analysing the effect of farmed fish on wild populations. Varying proportions of immature fish among escapees in rivers may, e.g. explain some of the disparity between the proportion of farmed fish and genetic introgression observed among Norwegian salmon populations (Diserud et al. 2022). In this study, 43% of fish where data on maturation status was available were immature upon recapture in the river, and the likelihood of being mature increased significantly with fish size. The proportion is even likely to be higher, as data on maturation status were missing from a large part of the smaller size classes caught with traditional fishing methods. Extensive recapture of immature farmed salmon has also been reported from the small Norwegian river Steinsdalselva (Madhun et al. 2015), and 41% of the fish caught in a fish trap in the river Etneelva during the period 2014–2018 were immature (Madhun et al. 2023). In the latter study, they used fatty-acid profiles to demonstrate that the majority of immature farmed salmon caught in the river Etneelva were categorized as "recent" escapes, whereas nearly all fish that were categorized as "early" escapes (i.e. having had a marine growth period) were found to be mature. However, the present study is the first to present such data from multiple rivers and a wide range in time, thus comprising recaptures of farmed fish originating from multiple escape events, demonstrating that immature farmed fish commonly enter Norwegian rivers.

The proportion of immature farmed fish caught during recapture efforts was much higher for traditional fishing methods (85%) than for spearfishing and other recapture methods during snorkelling (24%). This is likely because the traditional fishing, mostly using rods, often takes place in the river mouth and lower parts of the rivers, where the relative numbers of farmed fish compared to wild fish are high, reducing the risk of bycatch of wild fish. From our experience after more than a decade of snorkelling and spearfishing, immature farmed fish are frequently observed in the estuary/river mouth and do not necessarily migrate far up the rivers. This is in accordance with the findings of Madhun et al. (2023), who collected escaped salmon below the trap at the river mouth of the river Etneelva, where the majority (22 out of 25) were immature escaped salmon. Thus, while immature farmed salmon appear to be attracted to freshwater, they seem to have a low motivation for traversing strong currents in the upstream direction, probably because they are not participating in spawning. In contrast, mature farmed salmon typically migrate long distances upstream, often until they face a migration barrier (Thorstad et al. 1998, Moe et al. 2016, Sylvester et al. 2018). This indicates that although the removal of farmed fish using traditional methods removes more escaped farmed individuals, targeted removal by snorkelling on the spawning grounds may have a larger ecological benefit per individual removed, as only mature fish pose a risk of genetic introgression. However, recapture of immature escapees is also valuable, as farmed fish may infect wild fish with pathogens upon entering rivers (e.g. Taranger et al. 2015), and may migrate to sea for then to return to spawn in subsequent years. Surveying estuaries with traditional methods may also detect recent escape

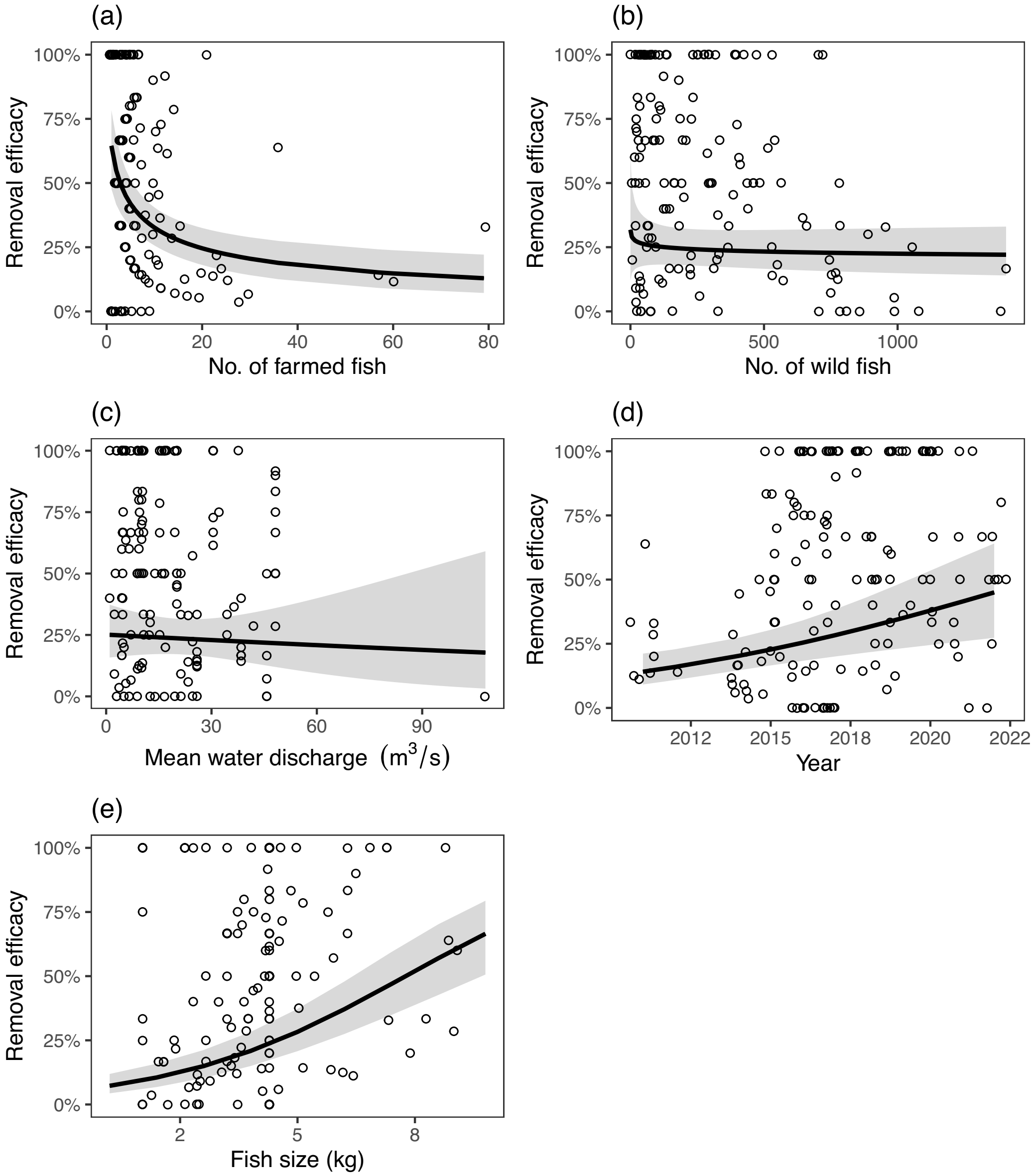

Figure 4. Relationship between farmed fish removal efficacy and the number of farmed fish in the river before removal (a), number of wild fish (b), mean water discharge (c), year (d), and estimated mean body size (e). The lines display the predicted relationships (with 95% confidence intervals) from the binomial GLMM model, while the points (jittered) display the data points for each of the surveys/removal attempts.

events and provide information about which rivers should be prioritized for snorkelling surveys to target mature escapees on the spawning grounds.

Efficacy of targeted removal efforts

More farmed fish were caught by traditional fishing techniques such as rod-fishing than by spearfishing during snorkelling in this study, but the latter method is better suited for surveying larger areas of rivers and can provide information on the total number of farmed and wild fish present. On average, 53% of farmed fish that were observed across snorkelling surveys were successfully removed. The efficacy during these removal attempts was significantly lower in rivers having a high number of farmed fish and increased with increasing fish size, but was not significantly related to the number of wild fish or river size. The last result may at first appear surprising, as it intuitively appears easier to hunt fish in smaller water bodies. However, the effects of river size are probably obscured by the relatively low (and possibly biassed) sample size of larger rivers in this material, as the method is mostly applied in small and moderately sized rivers. Most of the rivers in our study have an average discharge from 2 to 40 m^3 s^{-1}. Furthermore, there are several other factors that probably affect the efficacy of targeted removal efforts that are not included in the analysis. For example, the effort level likely varied considerably among the surveys included here, as the removal of farmed fish often was a secondary objective during drift diving censuses of the populations, and thus time available for removal efforts was often limited and variable. Furthermore, the method is generally limited to relatively clear rivers and to periods with relatively low discharge, and the efficacy of spearfishing may be strongly affected by factors such as visibility, discharge, and habitat characteristics of the rivers.

Mahlum et al. (2019) demonstrated that skilled snorkelers can distinguish farmed salmon from wild salmon with high precision, but the precision is likely to be lower if the visibility is poor or if the farmed fish are intermixed in large schools of wild fish. Furthermore, the characteristics of farmed fish vary among individuals, and are often less distinctive in fish that escaped early and have had a long life in the wild (Fleming et al. 1994). As a result, some farmed fish may be difficult, if not impossible to distinguish solely based on visual characters, particularly under less-than-ideal conditions. Thus, snorkelling surveys may, in some cases, underestimate the total number of farmed fish, resulting in a possible overestimation of true recapture efficacy. Furthermore, both visual identification of farmed fish and successful spearfishing are skills that require experience. Spearfishing efficacy increased significantly during our 12-year study period, possibly because the crew got more experience. However, this may also in part be an effect of more time on average spent hunting farmed fish during each survey, as the removal of farmed fish has received more funding in Norway during the study period, resulting in spearfishing more often being a priority during snorkelling surveys.

The number of fish recaptured from the rivers using a combination of methods (2445 farmed Atlantic salmon) only encompass a small fraction of the total number of escaping fish in this region. According to the official escape statistics, escapes of nearly 500 000 Atlantic salmon from aquaculture were reported during 2011–2021 in the regions covered in this study (Norwegian Directorate of Fisheries 2024c). This is likely to be an underestimate as not all escape incidences are detected and reported. There are several possible explanations for the disparity between numbers of fish escaping vs. recaptures. First, recapture is in many cases performed using gillnets in the marine environment adjacent to known escape incidences, catching many fish before they reach the rivers (Dempster et al. 2018). Second, the freshwater removal efforts do not cover all rivers in the region. Third, and likely most important, escaped farmed fish are often found to suffer high mortality in the marine environment prior to entering rivers. Fish can escape at different times during the production cycle, and the marine mortality is likely to be high for fish escaping early in the production period, i.e. during the smolt and post-smolt stages (Skilbrei et al. 2015), or if they escape out-of-season in relation to natural migratory patterns of wild fish (Skilbrei 2013). In contrast, mature fish escaping late in the production cycle or from brood-stock facilities may enter rivers directly after escaping, and are thus more likely to spawn (or be recaptured) in the rivers. Consequently, escape events involving large, mature fish may constitute a particularly high risk with regards to genetic introgression and should be a particular focus with regards to removal efforts.

All available methods for recapture of escaped farmed fish entail some risk of bycatch and damage to wild fish. In the present dataset, 90 wild salmon and 2 sea trout were reported killed during removal activities. The most common reason for casualties was fishermen misidentifying wild fish as farmed. This can occur if the fish has lesions, injuries, or other morphological deviations that may be wrongly interpreted as farm characters. Also, repeat spawners or fish originating from hatcheries may have several "farm-like" characteristics, such as deviant spot patterns and fin erosion. Casualties were also caused by wild fish being euthanized due to injuries sustained during rod fishing. In general, casualties were more common during traditional fishing than removal during snorkelling, which likely reflects that the snorkelling is usually performed by more experienced personnel and that the snorkelling approach is less likely to result in bycatch. The casualties from rod fishing may also be higher than reported, as the fate of wild bycatch that were subsequently released are not known in this study. Survival of salmon that are released after angling is usually high, but post-release mortality may increase if temperatures are high or the fish unproperly handled (Van Leeuwen et al. 2020). The wild fish casualties were nonetheless few relative to the number of farmed fish caught in this study, but the risk of bycatch should be evaluated when planning removal programmes.

Concluding remarks

Various efforts to limit escape events have resulted in significant reductions in both reported numbers of escapees (Norwegian Directorate of Fisheries 2024c) and the occurrence of farmed fish in rivers in Norway in recent years (Glover et al. 2019). The risk of further introgression can be mitigated by implementing improved technical standards that further reduce the numbers of escapees, or by establishing reproductive barriers such as the production of sterile fish that prevent interbreeding with wild conspecifics (Glover et al. 2020). However, farmed salmon are still escaping and finding their way into rivers.

Based on experience spanning 12 years and 63 Norwegian rivers, the current study demonstrates that it is possible to recapture a considerable number of escaped farmed fish in rivers by removal using both spearfishing during snorkelling and traditional fishing methods. The study also reveals that different fishing methods caught different size groups and farmed fish with different reproductive maturation statuses. While a larger overall number of farmed fish were caught by traditional fishing techniques than by snorkelling, the snorkelling approach resulted in the capture of larger fish, which were more often mature and thus arguably have a larger ecological impact than smaller, immature escapees. Thus, different methods may complement each other, and methodological approach should be considered depending on size and maturity of targeted fish when planning removal efforts. We therefore conclude that until more permanent solutions that can minimize the impacts of farmed fish are implemented, targeted removal efforts in rivers represent an important strategy to reduce the impacts once the escapes have occurred.

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Author contributions

Conceptualization: H.S. and K.W.V. Data curation: H.S. and K.U., Methodology: H.S., T.W., E.S.N., and G.B.L. Formal analysis: H.S. Project administration: H.S., B.T.B., and G.B.L. Investigation: H.S., E.S.N., T.W., G.B.L., M.K., K.U., B.T.B., and K.W.V. Writing – original draft: H.S. Writing – review and editing: K.W.V. and M.K.

Supplementary material

Supplementary material is available at *ICES Journal of Marine Science* online.

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Data availability

The data underlying this article are available in the supplementary material.

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