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Recapture of cultured salmon following a large-scale escape experiment

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ABSTRACT: A large-scale escape experiment using 1031 adult Atlantic salmon *Salmo salar* L. was performed in the Hardangerfjord in western Norway to study the dispersal of escaped salmon, evaluate the effect of a gill-net fishery targeting escaped salmonids and test whether surface trawling is an effective way of recapturing escaped salmon in a large fjord system. The salmon of mean weights 1.56 and 5.5 kg were released from 2 commercial fish farms in late September 2006. All fish were tagged with external tags, and 48 were also equipped with acoustic transmitters. A surface pair-trawl (50 m wide and 8 m deep) was constructed to optimize catchability and maneuverability in the fjord environment. Trawling was unsuccessful, and caught only 6 simulated escapees. Telemetry data confirmed that the fish were available along the towing tracks, and we assume that towing speed and/or trawl size may have been suboptimal with regard to avoidance by fish in the fjord environment. Gill-netting proved to be an efficient method of recapture. The total reported recapture rate (of 114 fishers) was 40%, but a significantly higher recapture rate (67%) of the more highly rewarded acoustic transmitters, and the distribution of the fish in time and space, suggest that the actual catch may have been substantially higher. Approximately 90% of the catches were taken within 40 km of the release sites over the course of 4 wk. We conclude that a significant proportion of escaped adult salmon can be recaptured if the catch effort within the fjord basin is widespread and lasts for at least 4 wk.

KEY WORDS: Escaped cultured salmon · Fish farms · Recapture · Gill-net · Trawling

INTRODUCTION

Farming of Atlantic salmon has grown rapidly since the mid-1960s, and farmed salmon that escape from cages have become a serious problem for the fish-farming industry and for the conservation of wild stocks. Farming has been correlated with declines in natural populations (Ford & Myers 2008). Escapees may spread diseases and parasites and interfere with the genetic make-up of wild stocks if they manage to interbreed (Lura & Sægrov 1991, McGinnity et al. 2004, Naylor et al. 2005, Hindar et al. 2006, Jonsson & Jonsson 2006, Skaala et al. 2006, Ferguson et al. 2007, Skilbrei et al. 2010).

Technical and operational failures of fish-farming equipment are the main causes of the escape events reported to the Norwegian Directorate of Fisheries (Jensen et al. 2010); numbers have varied from less than 200 000 to more than 900 000 individuals yearly from 2001 to 2009 (www.fiskeridir.no). It is anticipated that the total numbers of escapees may be considerably higher than those reported (Baarøy et al. 2004). Small-scale unreported escape events may make up a large portion of the escaped farmed fish (Skilbrei & Wennevik 2006), and genetic assignment (Glover et al. 2008) has recently been developed as a tool to find the farm of origin of larger unreported escape events.

Escaped farmed salmon are present in the North Atlantic Ocean (Hansen et al. 1997) and in rivers and coastal fisheries of neighboring countries wherever salmon are cultured (Lund et al. 1991, Carr et al. 1997, Walker et al. 2006). They are also present along the North American west coast (McKinnell et al. 1997, Volpe 2000). Little effort has been made to compare the efficiency of different fishing gears and to develop methods and strategies for recapture of fish that have escaped. It has been proposed that recapture strategies using biological cues to stimulate the fish to return

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to cages could be developed for additional growth and lower economic losses (Bridger & Garber 2002). Tlusty et al. (2008) showed that acoustic conditioning may have the potential to recall and/or reduce the spread of escapees.

Temporal variation in the catches of escaped farmed salmon in the sea has been related to escape events (Crozier 1998), and gill-nets appeared to be a successful gear during recapture efforts in British Colombia, Canada (Morton & Volpe 2002) and in Chile (Soto et al. 2001). In many regions of Norway, a gill-net fishery targeting escaped cultured salmonids in the sea is encouraged from 1 October to 28 February. After examining the catch statistics for this seasonal fishery, Skilbrei & Wennevik (2006) observed that the catch per unit effort responded to local escape incidents, but they were unable to quantify the catch efficiency of the fishery.

While released triploid steelhead trout *Oncorhynchus mykiss* Walbaum remain in the vicinity of a farm for at least 1 mo (Bridger et al. 2001), released Atlantic salmon may move rapidly away from the cage site (Whoriskey et al. 2006, Skilbrei et al. 2010). However, they remained long enough in one large Norwegian fjord for catches to be made: high recapture rates (16 to 63 %) of released salmon were demonstrated in a simulated escape study after release of a small number of fish equipped with acoustic transmitters (Skilbrei et al. 2010). The high recapture rates were probably possible because the fish showed a strong tendency to move close to the surface (Skilbrei et al. 2009), thereby increasing their likelihood of being taken in gill-nets (Skilbrei et al. 2010). It is not known whether larger groups of escaped salmon behave differently from the fish reported in these previous studies, in which only a limited number of fish were released simultaneously.

Based on these behavioral observations, surface trawling appears to be a suitable method for the recapture of escapees. A surface trawl can cover a large area in a short period of time, and may therefore be useful for the recapture of salmon that have dispersed widely and are swimming close to the surface. Trawls have been used to catch young salmonids along the continental shelf of western North America (Trudel et al. 2009), for research trawling in the Bering Sea (Radchenko & Mathisen 2004, Fukuwaka et al. 2008) and for the capture of postsmolts in the Norwegian Sea (Shelton et al. 1997, Holm et al. 2000); adult salmon have been taken as bycatch in trawling on the Newfoundland continental shelf (Lear 1976). Although trawling has several applications in salmon research, this method has not yet been tested for the purpose of catching escaped adult salmon.

To add to our knowledge of the behavior of escaped salmon, and to be able to develop and improve recapture strategies, we (1) studied the dispersal of the fish following more realistically scaled escape incidents, (2) evaluated the effect of a gill-net fishery targeting escaped salmonids in a large fjord system and (3) tested whether surface trawling is effective as a means of catching escaped salmon.

MATERIALS AND METHODS

Study area. There is a large aquaculture industry in the Hardangerfjord in western Norway (Fig. 1). The total production of salmon from ca. 50 locations was close to 40 000 t in 2003 (Skilbrei & Wennevik, 2006), and exceeded 58 000 t in 2008 (Norwegian Directorate of Fisheries). The halocline in the fjord varies greatly in thickness, temperature and salinity over the course of the year, but is typically between 5 and 10 m during summer and autumn (Skilbrei et al. 2009). A grid of acoustic receivers had been installed and used for telemetry experiments in the fjord system (Skilbrei et al. 2010) (Fig. 1). Capture of escaped cultured salmonids was le-

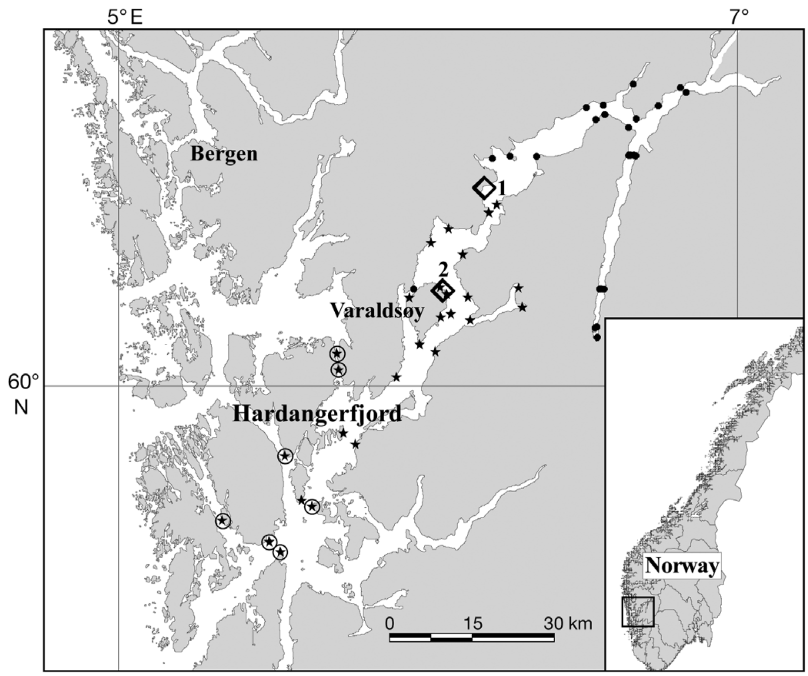

Fig. 1. The locations of the acoustic receivers (black stars and filled circles, operated by the Institute of Marine Research and the Norwegian Institute of Nature Research, respectively) in Hardangerfjord, and the 2 cage release sites R1 and R2 (1 and 2, diamonds). The 'outermost' receivers (see 'Materials and methods') are circled

galized in the fjord from 1 October 2006 to 28 February 2007 by permitting the use of floating gill-nets that are otherwise prohibited to conserve the stocks of wild salmon during their spawning migration.

Fish tagging and releases. Almost 1000 adult salmon were tagged with T-bar anchor tags (Hallprint) in 2 commercial farms (see Fig. 1 for their locations) in late September 2006. The average size of the fish tagged was 76 cm at Farm 1 (release R1) and 49 cm at Farm 2 (release R2). Equal numbers were tagged at each farm (Table 1). A further 48 fish were equipped with acoustic transmitters carrying a depth sensor (V13P-1L-S256 coded pingers, 45 mm long, weight in water 6 g, 40 to 120 s delay randomised between pings; Vemco) following the tagging procedure described in Skilbrei et al. (2009). The experiment and the tagging procedure were approved by the Norwegian committee for the use of animals in scientific experiments (FDU).

The letters HI (Norwegian acronym for the Institute of Marine Research), the IMR internet address (imr.no) and postal code were printed on the T-bar tags, in addition to an individual alphanumeric code. No information for the public was given on the acoustic pinger, apart from an individual number. The reward was 100 Norwegian Krone (NOK) per T-bar anchor tag returned, and 500 NOK for an acoustic tag. Information about the pinger and the reward was available on the IMR Internet home page. Information about the release experiments was also given in 2 articles in the largest regional newspaper during 2006.

Trawl recapture experiment. The pelagic trawl used was a 4-panel design with a circumference of 206 m. Mesh size at the front was 1200 mm, tapering to 60 mm in the extension. The codend had a mesh size of 60 mm. The trawl was made of black, impregnated Dynema rope. To float the trawl, 12 canvas kites (50 × 50 cm) were mounted around the centre of the headline at 40 cm intervals. Four cylindrical floats were also attached to the float line: 2 at the centre and 1 at the tip of each wing. The trawl was fished with 300 m long sweeps. The upper sweep consisted of a 10 mm Dynema rope and the lower of 12 mm wire. Weights of 40 kg were attached to each of the lower wings.

The trawl was operated as a pair-trawl and was towed by a pair of 15 m fishing vessels, with main engines of 295 kW. During towing the distance between the vessels averaged 35 m (range 25 to 50 m), and towing speed ranged from 3.8 to 4.2 knots. The vertical trawl opening was measured at 7 to 8 m and the horizontal (wing distance) at 35 to 40 m.

For practical and safety reasons, pelagic trawling took place during the daytime, but was continued until after dusk on some days. Six hauls of a total duration of 29 h 5 min were conducted on 4 d from 27 September to 1 October 2006 (Table 2)

A triangular aluminium frame carrying an SIT underwater video camera was inserted between the extension and the codend to study the passage of fish into the codend in real time. The camera was connected by cable to a video link on top of a small raft attached by ropes to the trawl and towed along with it.

Data treatment. To enable comparison of the data with that of earlier telemetry experiments in the fjord, the computations were done according to Skilbrei et al. (2009, 2010). To study the fine-scale movements of the fish close to the surface, recordings of swimming depth were classified into 2 categories: movements above 15 m depth, where the fish spend most of their time, and diving below 15 m depth. If the last detection of a fish was made by the acoustic receivers closest to the mouth of the fjord (see Fig. 1) it was assumed that the fish moved out of the fjord on that date. A fish that was not reported captured but had not moved out of the fjord (see above)

Table 1. *Salmo salar.* Dates of tagging and releases from the 2 release sites (R1 and R2), length and weight of fish and numbers tagged and recaptured (%). The numbers of fish that disappeared within, or moved out of, the area are also reported for the fish tagged with acoustic transmitters

	Release site R1	Release site R2	Total
Date of tagging	20.09.06	21.09.06	
Date of release	26.09.06	27.09.06	
Acoustically tagged fish			
Mean length in cm (SD)	76.2 (4.3)	49.1 (4.2)	
Mean weight in kg (SD)	5.51 (0.99)	1.56 (0.40)	
Released	25	23	48
Captured (%)	19 (76)	13 (57)	32 (67)
Moved out (%)	2 (8)	4(17)	6 (13)
Disappeared (%)	4 (16)	6 (26)	10 (20)
T-bar anchor-tagged fish			
Mean length in cm (SD)	75.4 (6.2)	49.0 (4.5)	
Mean weight in kg (SD)	5.45 (1.35)	1.56 (0.48)	
Released	468	515	983
Captured (%)	201 (43)	188 (37)	389 (40)

Table 2. Overview of hauls made with the pelagic trawl and the catch and numbers of fish observed escaping from the trawl per haul. One of the salmon caught was from release R1 (Haul 6), 5 were from R2 and 1 was untagged. Hauls 3, 4 and 6: large quantities of seaweed

Haul	Date (d.mo.yr)	Start (local time)	Duration (h)	No. of salmon Caught	No. of salmon Escaped
1	27.09.2006	09:30	04:50	2	1
2	27.09.2006	17:45	03:00	0	0
3	29.09.2006	08:45	09:05	1	1
4	30.09.2006	13:00	06:30	1	1
5	01.10.2006	13:25	03:00	1	1
6	01.10.2006	18:20	02:40	1	2

was classified as 'disappeared' from its last detection date. A fish was assumed to be present in the fjord from the day of release until the date before its last detection or of its reported recapture in the fjord. To calculate the estimated position of a fish that was not within the range of a receiver at 12:00 h on selected dates, it was assumed that it had swum at constant speed from the previous to the next receiver, taking the shortest possible route.

The diurnal cycle was divided into daylight and night as follows: daylight, the period from sunrise to sunset; night, the period from the onset of nautical twilight in the evening to the end of nautical twilight in the morning. The computations of sunrise, sunset, and twilight times were made by the Online-Photoperiod Calculator V 1.94 L (www.sci.fi/~benefon/sol.html). A 2-tailed Student's *t*-test was used to test whether the means of the mean individual swimming depth (no. of detections > 20 per individual) at night and during the day differed. Only detections at depths of less than 15 m were used for these comparisons.

A *G*-test (Sokal & Rohlf 1981) was employed to test whether the number of fish reported as captured differed between groups. The effects of maturity, release site and tag type were tested in separate tests.

RESULTS

Fish equipped with acoustic transmitters

One individual remained at depths of 60 to 111 m during most of the day following R2. The others swam at a mean depth of 6.3 m for the first hour after release at 09:00 h, when the first trawling started (Table 2), and moved gradually closer to the surface during the next 10 h; hourly means ranged from 4.1 to 4.7 m after 2 to 4 h, and 1.6 to 2.1 m after 7 to 10 h.

During the period from Day 2 to 60, the large (R1) fish stayed above 15 m depth for 83% of the time during the day, and 85% of the time during the night. The grilse-sized fish (R2) spent 96% of the time during the day, and 100% of the time during the night above 15 m depth. The mean swimming depths in this part of the water column were 0.3 ± 0.4 (± SD) m for the R1 group and 0.9 ± 1.1 m for the R2 group at night; the difference was not statistically significant. They swam significantly deeper during daytime, at 1.4 m ± 1.2 and 2.5 ± 1.4 m depth, respectively ($p < 0.05$, *t*-test).

Most of the captures were reported during the first 40 d after release (Fig. 2). Ten of the 22 fishers who returned transmitters did not report catches of T-bar anchor tagged fish. Only 6 fish were categorized as having left the area, 3 of them during the first 60 d (Table 1, Fig. 2). On the basis of their appearance (brownish colour, extended lower jaw), 4 of the 48 fish released were maturing males. One of them disappeared after 3 d, 1 was recaptured after 9 d, 1 left the fjord after 15 wk and 1 moved rapidly up the fjord and was observed for the last time after 6 d, 70 km distant, at the receiver close to the estuary of the river Opo in the innermost part of the fjord covered by the receivers (see Fig. 3; fish approaching the river).

Catches in trawl

A total of 1 tagged salmon from R1 and 5 from R2 were caught during the 6 hauls from 27 September to

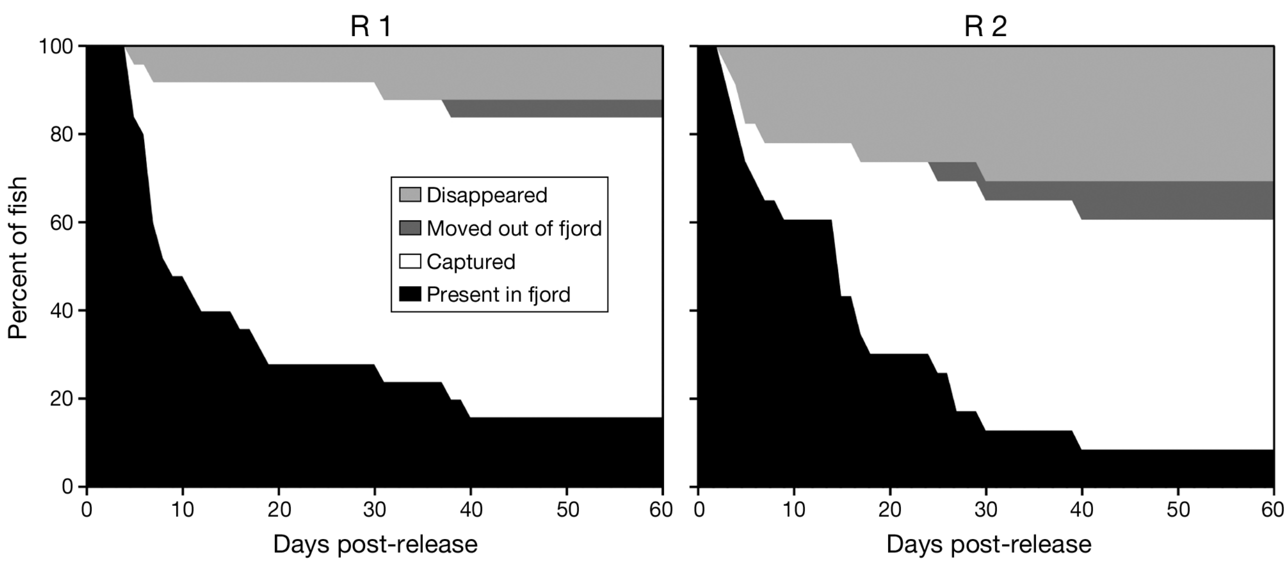

Fig. 2. *Salmo salar.* Stacked area plots showing the relative proportions of fish from releases R1 and R2 that remained in the fjord, were captured, moved out of the fjord or disappeared as a function of days post-release

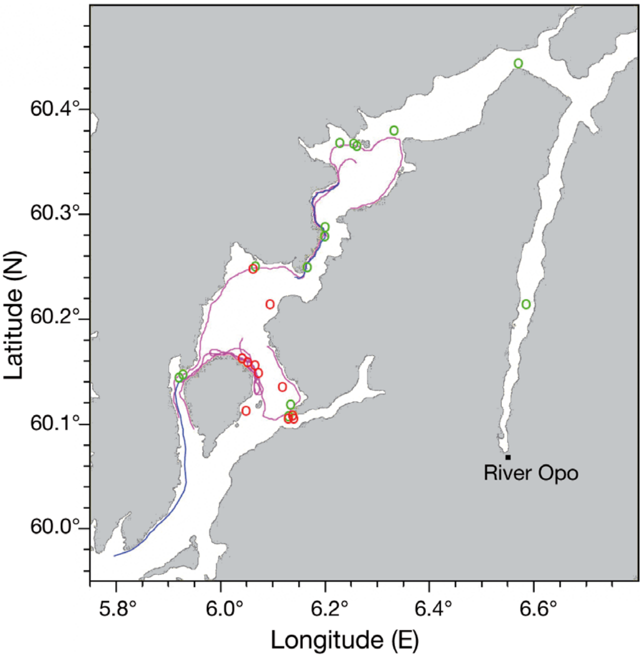

Fig. 3. Towing tracks (coloured lines) for the hauls made with the pelagic trawl in the Hardanger fjord. The 2 hauls made on 1 October 2006 are marked with a blue line to facilitate comparison of tracks with estimated positions at 12:00 h on the same day of transmitter-tagged Atlantic salmon from releases R1 (green circles) and R2 (red circles)

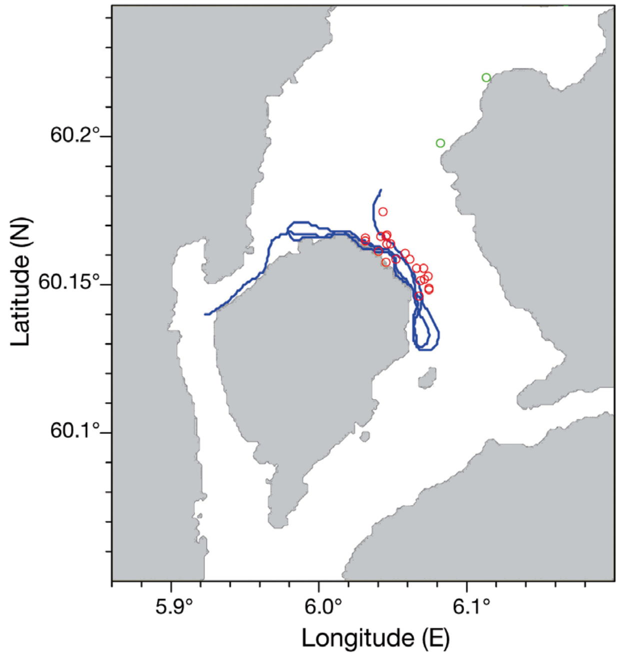

Fig. 4. Towing track (solid blue line) for Haul 1 made on 27 September between 09:30 and 14:20 h and estimated positions at 12:00 h on the same day of Atlantic salomon with acoustic transmitters from releases R1 (green circles) and R2 (red circles)

1 October 2006 (Table 2, Fig. 3). The towing track of the trawling performed immediately after release R2, and hauls at later dates, appeared to match the geographical distribution of the fish equipped with acoustic transmitters (Figs. 3 & 4). In addition to the 6 salmon, 1 untagged salmon was caught, as well as mackerel *Scomber scombrus* and garfish *Belone belone*. Another 6 salmon and several smaller groups of large mackerel that had passed the camera frame were observed to swim forward past the camera again and never re-entered the codend (Table 2). These fish thus likely escaped by out-performing the trawl. During some hauls, large amounts of drifting seaweed (mainly *Ascophyllum nodosum*) and some floating debris entered the trawl (Table 2). This partly clogged meshes, increased the towing resistance of the trawl and consequently reduced towing speed. The trawl therefore needed to be cleaned about once a day.

T-bar tag recoveries

Reports of catches of 389 T-bar anchor-tagged fish were received from 104 fishers. A total of 94.9% of the recoveries were reported from recreational fishers using gill-nets (336 out of 354 tag reports that provided information about fishing method), while anglers reported 5.1%. A range of gill-net types were used: floating nets, trammel nets and bottom-set nets. Only one third reported the type of gill-nets used. Of these, 50% used bottom-set and 20% used trammel nets. When specified, mesh sizes ranged from 52 to 70 mm, and the nets were of standard length (27.5 m). All rod catches were reported from estuarine areas. One tag was reported from freshwater.

The recapture rate of fish with acoustic tags was 67%, significantly higher than the 40% recapture rate of T-bar tagged fish (*G*-test, $p < 0.05$; Table 1). The release site did not statistically influence the catch rate of either acoustic or T-bar tagged fish. More than 90% of the recaptures were taken in the middle section of the Hardangerfjord (Fig. 5) within 40 km of the 2 release sites during the first 4 wk post-release (Fig. 6). The recapture of mature males (5 of 33) was significantly lower than that of immature fish (384 of 950) ($p < 0.025$).

Three of the fishers that used floating gill-nets reported catch data and took scale samples (for check of wild versus farmed salmon) of both tagged and untagged salmon during the period from 1 to 21 October 2006. All of the 146 salmon they recaptured were farmed, but 81 of them were untagged fish of unknown farm origin. No reports of escapements were filed to the authorities during autumn 2006 from fish farmers in the area.

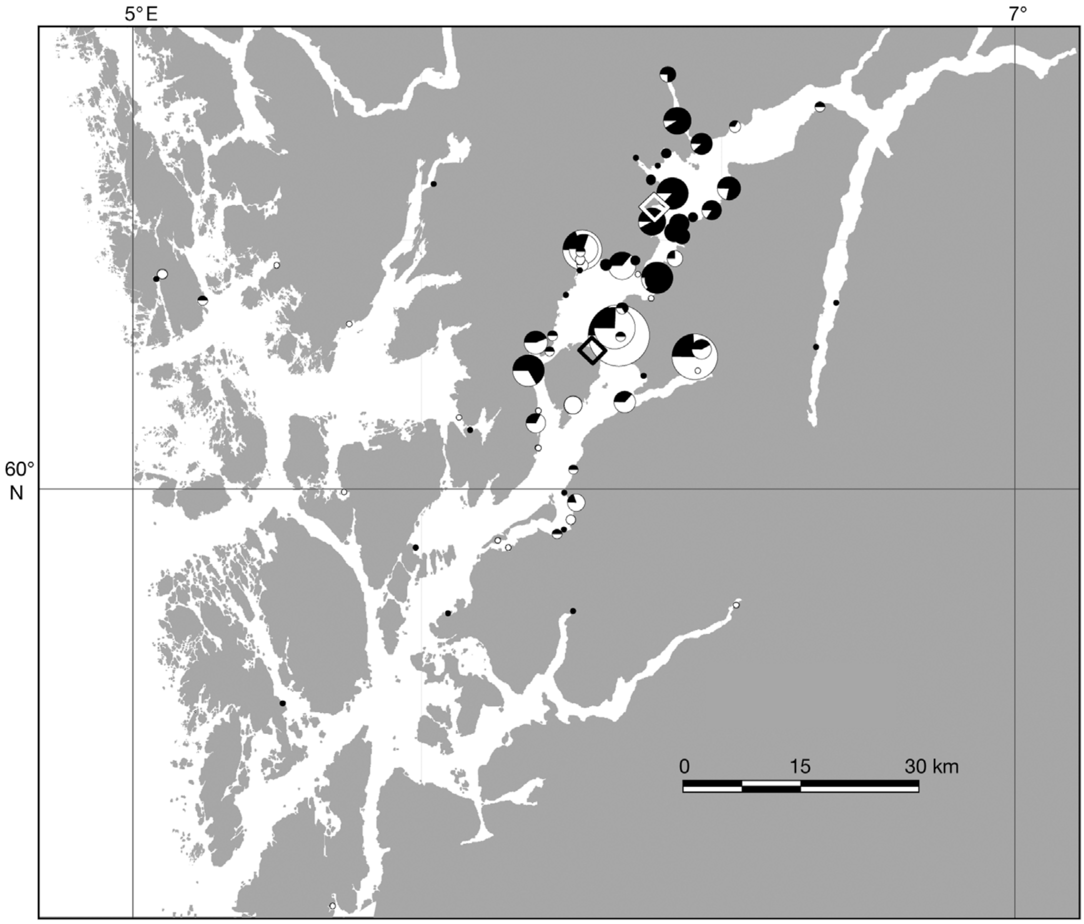

Fig. 5. *Salmo salar.* Sites of salmon catches. Pie charts showing number of fish (ranging from 1 to 46 ind.) from release R1 (black) and release R2 (white). Release sites are marked with white and black diamonds

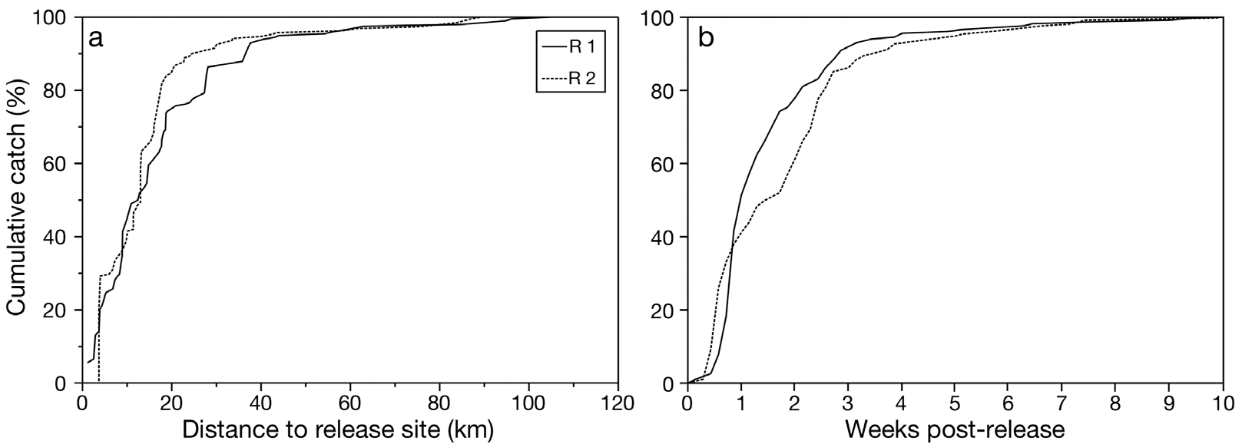

Fig. 6. *Salmo salar.* Cumulative catch versus (a) distance from the release sites and (b) weeks post-release for releases R1 and R2

DISCUSSION

This study of 2 realistically scaled escape incidents in a large fjord shows that a high percentage of both medium-size and large adult salmon were gill-netted within 40 km of the release site over the course of 4 wk, and that surface trawling was an ineffective method for recapturing escapees in a fjord environment.

The post-release behaviour of the fish equipped with acoustic transmitters was similar to that observed in previous studies in Hardangerfjord, when limited numbers were released (Skilbrei et al. 2009, 2010); the majority stayed within the fjord basin for several weeks and swam close to the surface above the halocline, especially at night. The recapture rate of these fish (67%) was also comparable to that of a small-scale release the previous autumn (62.5%; Skilbrei et al. 2010). Although the numbers were small, the significantly lower catch rate of mature males suggests that they behave differently from immature fish. Reduced catchability in the sea is to be expected if some of the mature, or maturing fish, enter freshwater. This behaviour was probably displayed by one of the fish equipped with an acoustic transmitter.

The evaluation of the data indicates that the overall recapture rate may have been higher than 50% in the fjord system. The recapture rate of fish with acoustic transmitters and those tagged with only T-bar anchor tags differed substantially (67 and 40%, respectively). The possibility that fish carrying acoustic tags had a higher catchability is difficult to evaluate and less likely than the alternative explanation: that the rate of reporting of a high-reward tag is clearly higher than that of the standard-reward tag (Pollock et al. 2001). Besides, the acoustic transmitter may have aroused the curiosity of the fisher and his motivation for reporting it. The fact that almost half of the fishers who returned transmitters did not report T-bar anchor tagged fish, which were nearly 20 times as abundant in the fjord, also suggests that the reporting rate was skewed in favour of the fish equipped with transmitters. The low percentage of acoustically tagged fish migrating out of the fjord and the low number of reported catches farther than 40 km away from the release sites also support the idea that most of the fish did not leave the area, and that a good deal more than 40% of the released fish were recaptured in the fjord. The high recapture rate may partly explain the lack of reports of fish being caught after a longer time, or farther away. It is also possible that the long-term survival may have been low, as in other release experiments in which the recapture of released adult fish was restricted to the first months post-release (Hansen 2006, Skilbrei et al. 2010).

The present experiment confirms the findings of studies in Chile (Soto et al. 2001) and Canada (Morton & Volpe 2002) showing that gill-netting may be efficient to recapture escaped salmon. The dispersal rate of the fish will probably influence the success of the fishery. If the fish remain in the vicinity of the farm, as escaped steelhead trout (Bridger et al. 2001) and salmon conditioned to acoustic signals (Tlusty et al. 2008) may do, then recapture may be facilitated.

It is important that a fishery for escaped salmon is regulated to efficiently target the fish that have escaped, and that it is monitored to see whether the catch of wild salmon and other species is acceptable or not. Skilbrei & Wennevik (2006) observed that floating gill-nets were the most commonly used gear in this fishery, that wild sea trout *Salmo trutta* were captured in the smaller-mesh-sized gill-nets, and proposed that it may be appropriate to regulate the mesh size allowed. The use of floating and bottom-set nets in shallow water and in the littoral zone may potentially catch a wide range of fish and crustacean species, and may have undesirable negative effects on other populations. For example, the spawning stock of coastal cod *Gadus morhua* is structured into local fjord populations (Jorde et al. 2007, Westgaard & Fevolden 2007) and has declined in recent years (Berg 2006). A moderate non-selective fishery may have a long-term effect on population growth rate of cod in fjords (Salvanes 2001). We recommend that the fishery for escaped farmed fish is regulated according to the size of the fish that have escaped, and also that different gear and gill-net types and the expected distribution with depth of the escaped fish are considered to minimize the bycatch of other species. For example, the use of indiscriminant bottom gill-nets as trammel nets may not be recommendable. If an escape event occurs close to salmon rivers during the period of spawning migration, then other gear types like bag-nets may be preferable.

Extensive pelagic trawling resulted in the capture of only 6 tagged salmon. However, the data indicate that the tagged fish were available for capture by the trawl. First, the trawling took place in the sections of the fjord with the highest abundance of tagged fish, as verified by acoustic telemetry and the recreational gill-net fishery. Second, most of the fish swam at a depth well within the vertical range of the trawl (7 to 8 m).

A tentative explanation for the low catch rates of pelagic trawling is that salmon avoided the approaching vessels and trawl, e.g. by diving. Previous experiments have shown that escaped cultured salmon can make rapid descents (Skilbrei et al. 2009). Although a pair-trawl was used in this study and the towing vessels therefore move beside the trawl path, the vessels were only 35 to 40 m apart and vessel noise provides a strong stimulus for fish swimming in the surface layer. Other studies have suggested that the surface trawl missed the salmon at night because the headrope passed below them, usually at depths between 0.8 and 1.6 m. (Krutzikowsky & Emmet 2005). However, in our study, floats ensured that the headrope skimmed the surface, so this is an unlikely explanation for the low catch rates.

The video recording demonstrated that 6 salmon managed to escape capture after entering the aft sections of the trawl by outperforming it, i.e. swimming forward faster than the trawl. Towing speed was ~2 m s^{-1} (4 knots), roughly corresponding to 3–4 body lengths s^{-1} for the size range of fish used in this study.

The maximum sustained swimming speed of a 45 cm long salmon is ca. 2 body lengths s^{-1} (Tang & Wardle 1992), which agrees very well with the estimated maximum movement rate of released salmon in the Hardangerfjord (Skilbrei et al. 2010). However, the burst speed of wild salmon of ca. 50 cm length has been measured at as much as 4 m s^{-1} (Colavecchia et al. 1998), which is high enough to outperform the trawl. More salmon than those observed by the camera may have entered the trawl and subsequently escaped. Suboptimal towing speed is thus also a possible reason for the low catch efficiency. For comparison, a salmon research survey in the Bering Sea captured salmon from 30 to 70 cm length towing at 5 knots in the surface layer during daylight (Fukuwaka et al. 2008). Although our towing speed was suboptimal, a higher speed was not possible with our chartered vessels and trawl design, which was set up to permit high maneuverability. Salmon may also have moved too close to the shore to be captured by the pair-trawl. In another large Norwegian fjord, simulated escapees tended to move along the shoreline, with very few observations being made away from the shoreline (C. Chittenden pers. comm.). In this study, several of the recreational fishers who took part in the gill-net fishery in the experimental area reported that they caught tagged fish in the section of their nets close to the shore.

CONCLUSIONS

Our realistically scaled escape event experiments in the Hardangerfjord support earlier assertions, based on small-scale releases, to the effect that a considerable proportion of escaped adult salmon might be recaptured if the catch effort within the fjord basin is widespread and persists for at least 4 wk. The trawl used was ineffective in the fjord environment. A directed gill-net fishery would appear to have the greatest potential for recapturing substantial numbers of fish after an escape. It is also by far the cheapest alternative, but should be regulated to minimize negative effects on other populations and must normally be limited to areas and times of the year when conflicts regarding the conservation of wild salmonids are low. If an extensive and directed gill-net fishery is rapidly introduced into waters surrounding farms where salmon have recently escaped, then the risks of hybridization between cultured and wild salmon and the potential for spread of fish diseases are reduced.

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LITERATURE CITED

Baarøy V, Gjerde B, Heggberget TG, Jensen PE and others (2004) Identifisering av rømt oppdrettslaks. Utredning fra utvalg nedsatt av Fiskeridirektøren (identification of escaped farmed salmon. Report from Committee to the Director of Fisheries), Bergen, (in Norwegian)

Berg E (2006) Norwegian coastal cod. Fisken og havet. Særnummer (spec. edn) 2:66–67

Bridger CJ, Garber AF (2002) Aquaculture escapement, implications and mitigation: the salmonid casestudy. In: Costa-Pierce BA (ed) Ecological aquaculture, the evolution of the blue revolution. Blackwell, Oxford, p 77–102

Bridger CJ, Booth RK, McKinley RS, Scruton DA (2001) Site fidelity and dispersal patterns of domestic triploid steelhead trout (*Oncorhynchus mykiss* Walbaum) released to the wild. ICES J Mar Sci 58:510–516

Carr JW, Anderson JM, Whoriskey FG, Dilworth T (1997) The occurrence and spawning of cultured Atlantic salmon (*Salmo salar*) in a Canadian river. ICES J Mar Sci 54: 1064–1073

Colavecchia M, Katopodis C, Goosney R, Scruton DA, McKinley RS (1998) Measurement of burst swimming performance in wild Atlantic salmon (*Salmo salar* L.) using digital telemetry. Regul Rivers Res Manag 14:41–51

Crozier WW (1998) Incidence of escaped farmed salmon, *Salmo salar*, in commercial salmon catches and fresh water in Northern Ireland. Fish Manag Ecol 5:23–29

Ferguson A, Fleming I, Hindar K, Skaala Ø, McGinnity P, Cross TF, Prodöhl P (2007) Farm escapes. In: Verspoor E, Stradmeyer L, Nielsen JL (eds) The Atlantic salmon: genetics, conservation and management. Blackwell Science, Oxford, p 357–398

Ford JS, Myers RA (2008) A global assessment of salmon aquaculture impacts on wild salmonids. PLoS Biol 6: e33 doi:10.1371/journal.pbio.0060033.

Fukuwaka M, Azumaya T, Davis ND, Nagasawa T (2008) Bias in size composition of chum salmon (Oncorhynchus keta) caught by a gillnet with a geometric series of mesh sizes, and its correction using gear intercalibration. ICES J Mar Sci 65:930–993

Glover K, Skilbrei OT, Skaala Ø (2008) Genetic assignment identifies farm of origin for Atlantic salmon *Salmo salar* escapees in a Norwegian fjord. ICES J Mar Sci 65:912–920

Hansen LP (2006) Migration and survival of farmed Atlantic salmon (*Salmo salar* L.) released from two Norwegian fish farms. ICES J Mar Sci 63:1211–1217

Hansen LP, Reddin DJ, Lund RA (1997) The incidence of reared Atlantic salmon (*Salmo salar* L.) of fish farm origin at West Greenland. ICES J Mar Sci 54:152–155

Hindar K, Fleming IA, McGinnity P, Diserud O (2006) Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. ICES J Mar Sci 63:1234–1247

Holm M, Holst JC, Hansen LP (2000) Spatial and temporal distribution of post-smolts of Atlantic salmon (*Salmo salar* L.) in the Norwegian Sea and adjacent areas. ICES J Mar Sci 57:955–964

Jensen Ø, Dempster T, Thorstad EB, Uglem I, Fredheim A (2010) Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and methods to prevent escape. Aquacult Environ Interact 1:71–83

Jonsson B, Jonsson N (2006) Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. ICES J Mar Sci 63:1162–1181

Jorde PE, Knutsen H, Espeland SH, Stenseth NC (2007) Spatial scale of genetic structuring in coastal cod *Gadus morhua* and geographic extent of local populations. Mar Ecol Prog Ser 343:229–237

Krutzikowsky GK, Emmet RL (2005) Diel differences in surface trawl fish catches off Oregon and Washington. Fish Res 71:365–371

Lear WH (1976) Migrating Atlantic salmon (*Salmo salar*) caught by otter trawl on the Newfoundland continental shelf. J Fish Res Board Can 33:1202–1205

Lund RA, Økland F, Hansen LP (1991) Farmed Atlantic salmon (*Salmo salar*) in fisheries and rivers in Norway. Aquaculture 98:143–150

Lura H, Sægrov H (1991) Documentation of successful spawning of escaped farmed female Atlantic salmon, *Salmo salar*, in Norwegian rivers. Aquaculture 98:151–159

McGinnity P, Prodöhl P, Ó Maoiléidigh N, Hynes R, Cotter D, Baker N, O'Hea B, Ferguson A (2004) Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. J Fish Biol 65:173–187

McKinnell S, Thomson AJ, Black EA, Wing BL, Guthrie CM, Koerner JF, Helle JH (1997) Atlantic salmon in the North Pacific. Aquacult Res 28:145–157

Morton A, Volpe J (2002) A description of escaped farmed Atlantic salmon *Salmo salar* captures and their characteristics in one Pacific salmon fishery area in British Columbia, Canada, in 2000. Alaska Fish Res Bull 9:102–110. Available at: www.adfg.state.ak.us/pubs/afrb/afrbabst.php

Naylor R, Hindar K, Fleming IA, Goldburg R and others (2005) Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. BioScience 55:427–437

Pollock KH, Hoenig JM, Hearn WS, Calingaert B (2001) Tag reporting rate estimation: 1. An evaluation of the high-reward tagging method. N Am J Fish Manag 21:521–532

Radchenko VI, Mathisen OA (2004) Distribution, growth, and feeding of sockeye salmon in the western Bering Sea. Trans Am Fish Soc 133:606–621

Salvanes AGV (2001) Review of ecosystem models of fjords; new insights of relevance to fisheries management. Sarsia 86:441–463

Shelton RGJ, Turrell WR, Macdonald A (1997) Records of post-smolt Atlantic salmon, *Salmo salar* L., in the Faroe–Shetland Channel in June 1996. Fish Res 31:159–162

Skaala Ø, Wennevik V, Glover KA (2006) Evidence of temporal genetic change in wild Atlantic salmon, *Salmo salar* L., populations affected by farm escapees. ICES J Mar Sci 63:1224–1233

Skilbrei OT, Wennevik V (2006) The use of catch statistics to monitor the abundance of escaped farmed Atlantic salmon and rainbow trout in the sea. ICES J Mar Sci 63: 1190–1200

Skilbrei OT, Holst JC, Asplin L, Holm M (2009) Vertical movements of 'escaped' farmed Atlantic salmon (*Salmo salar*)—a simulation study in a western Norwegian fjord. ICES J Mar Sci 66:278–288

Skilbrei OT, Holst JC, Asplin L, Mortensen S (2010) Horizontal movements of simulated escaped farmed Atlantic salmon (*Salmo salar*) in a western Norwegian fjord. ICES J Mar Sci 67:1206–1215

Sokal RR, Rohlf JF (1981) Biometry. WH Freeman, New York, NY

Soto D, Jara F, Moreno C (2001) Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. Ecol Appl 11:1750–1762

Tang J, Wardle CS (1992) Power output of 2 sizes of Atlantic salmon (*Salmo salar*) at their maximum sustained swimming speeds. J Exp Biol 166:33–46

Tlusty MF, Andrew J, Baldwin K, Bradley TM (2008) Acoustic conditioning for recall/recapture of escaped Atlantic salmon and rainbow trout. Aquaculture 274:57–64

Trudel M, Fisher J, Orsi JA, Morris JFT and others (2009) Distribution and migration of juvenile chinook salmon derived from coded wire tag recoveries along the continental shelf of western North America. Trans Am Fish Soc 138:1369–1391

Volpe JP 2000. The occurrence of Atlantic salmon in coastal streams of southern British Columbia during 1999. British Columbia Ministry of Environment Lands and Parks Regional File Report. Nanaimo, BC

Walker AM, Beveridge MCM, Crozier W, O'Maoiléidigh N, Milner N (2006) Monitoring the incidence of escaped farmed salmon, *Salmo salar* L., in rivers and fisheries of the United Kingdom and Ireland: current progress and recommendations for future programmes. ICES J Mar Sci 63:1201–1210

Westgaard JI, Fevolden SE (2007) Atlantic cod (*Gadus morhua* L.) in inner and outer coastal zones of northern Norway display divergent genetic signature at non-neutral loci. Fish Res 85:306–315

Whoriskey FG, Brooking P, Doucette G, Tinker S, Carr JW (2006) Movements and survival of sonically tagged farmed Atlantic salmon released in Cobscook Bay, ME, USA. ICES J Mar Sci 63:1218–1223

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