

Research Article

Causal analysis of escapement of farmed salmonids in southern Chile

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ABSTRACT. Escaped salmonids are considered among the most serious threats to the aquatic environment. One hundred and nine escape incidents were reported in Chile from 2004-2021, representing some 8.53 million escaped salmonids. Of this total, 5.73 million were Atlantic salmon *Salmo salar* (67.2%), 0.83 million coho salmon *Oncorhynchus kisutch* (9.8%), and 1.96 million were rainbow trout *O. mykiss* (23.0%). It is estimated that 70.1% of the escaped salmonids were recorded in the Los Lagos Region, 23% in the Aysén Region, and 4.6% in the Magallanes Region. In total, 80.5% of the escapes were recorded from seawater facilities, while freshwater units accounted for 19.5%. The highest percentage of escaped salmon recorded in seawater over 2004-2021 was 1.71% of harvested salmonids in 2013. Some 39.5% of the escapes in 2015-2021 were attributed to rupturing of net cages, mainly due to adverse climatic conditions. The additional regulations introduced in 2020 by the Chilean authority, has helped to minimize the escape of farmed salmonids. As a consequence, just one escape event was reported in 2021, corresponding to 3.85% of the total number of escapees recorded from 2004-2021.

Keywords: farmed salmon; escaped fish; escape causes; regulations; environmental effects; southern Chile

INTRODUCTION

Escapes of farmed fish stocks from ocean-based rearing facilities in Chile are considered one of the main threats to the aquatic environment. However, unlike the northern hemisphere, the salmonids escaping from the cages in Chile are not native to the southern hemisphere. This study aims to document, for the first time, the number of escaped salmonids recorded in Chile in 2004-2021 and their causes. The Chilean government introduced the first salmonids stocks in 1875 to develop recreational fisheries (Basulto 2003, Dazarola 2019). Between 1886 and 1889, the eggs and fry of a wide range of salmonid species were imported from Europe. Many of these species failed to establish at that time. The first eggs of Atlantic salmon (*Salmo salar*), brown trout (*S. trutta*) and rainbow trout (*Oncorhynchus mykiss*), and were imported in 1904.

Efforts commenced in the same year to establish these species in the rivers of the south-central part of the country. In 1924, eyed ova of Chinook salmon (*O. tshawytscha*) were first imported from the USA and introduced into the rivers Maullín, Cochamó, and Puelo, in southern Chile (Los Lagos Region) (Fig. 1) (Basulto 2003, Dazarola 2019).

In 1930, 114,000 fertilized eggs of sockeye salmon (*O. nerka*); 200,000 eggs of Chinook salmon (*O. tshawytscha*); 225,000 eggs of coho salmon (*O. kisutch*); 250,000 eggs of white fish (*Coregonus clupeaformis*) and 200,000 eggs of lake trout eggs (a species of char, *Salvelinus namaycush*), were imported from the USA. Between 1968 and 1971, 2,415,000 eyed eggs of coho and Chinook salmon were imported from Washington State (Department of Fisheries), USA (Basulto 2003, Dazarola 2019).

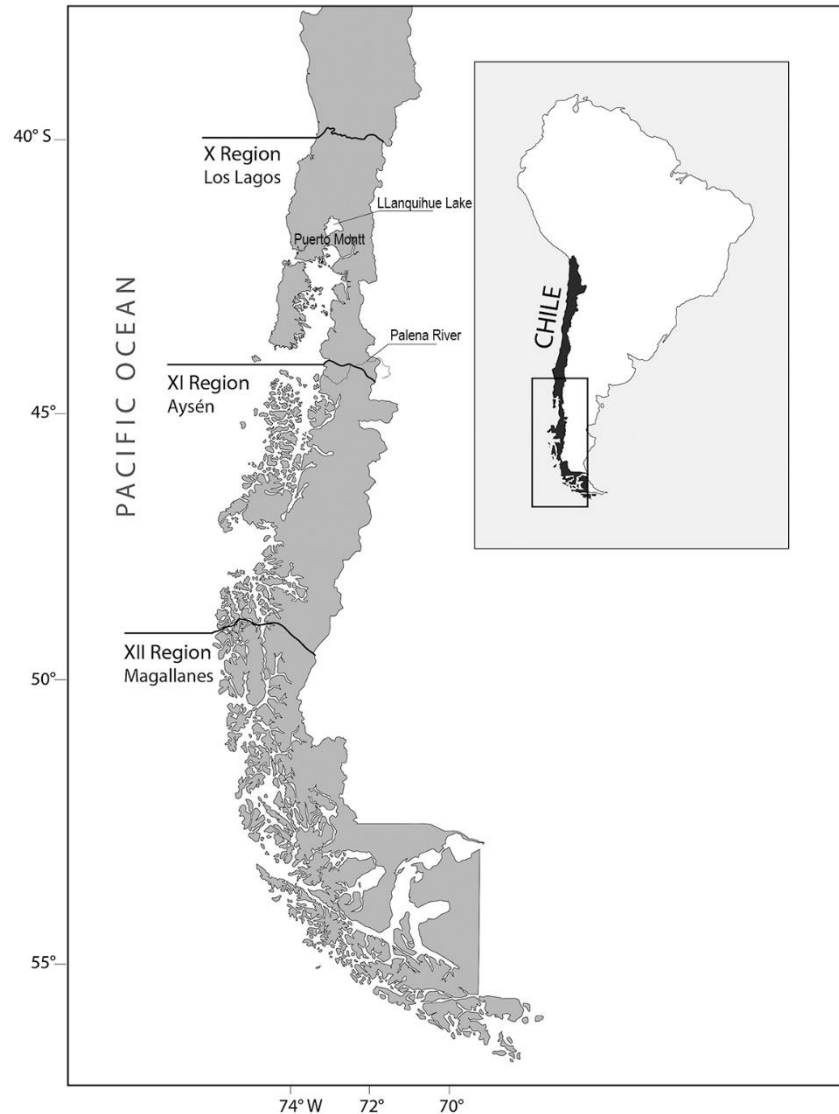


Figure 1. Regions where farmed salmon are produced in sea cages in Chile.

Salmon ranching was initiated in Chile in 1974. Between the mid-70s and 1987, some 40 million eyed eggs of cherry salmon (*O. masou*), pink salmon (*O. gorbuscha*), and chum salmon (*O. keta*) were imported from Japan into the Aysén Region, which resulted in the release of 26 million Pacific salmon fry (Méndez & Munita 1989). However, the expected returns were not achieved from these releases. In parallel, a joint venture between Fundación Chile and Domsea Farms also embarked on a ranching program using both coho and Chinook salmon. Between 1978 and 1982, they released 600,000 coho smolts and 400,000 Chinook smolts on Chiloe Island (Los Lagos Region). The first return of Chinook salmon was recorded in 1979, and yearly returns were recorded until 1991. The last attempt to ranch with coho and Chinook salmon was in

1982-1989 when 820,000 smolts were released in the Chiloe Island area in Los Lagos Region, 1,070,000 smolts in Aysén Region, and 4,057,000 smolts in Magallanes Region (Méndez & Munita 1989).

Salmon farming activity commenced at the end of the 1970s, with the production of coho salmon in sea cages by two companies, Nichiro Chile Ltda. and Mytilus S.A. This initiative represented the humble beginnings of the salmon farming industry in Chile. In the first years of Nichiro Chile's operation, the authorities instructed the company to release 10% of its coho salmon fry production into the Correntoso River (Puerto Montt, Los Lagos Region). Thus, 32,000 coho fry were released in 1980 and 10,000 in 1981. However, this requirement was revoked in 1982 (Méndez & Munita 1989). Once salmonid farming in

Chile was firmly underway, the riverine stocking program with salmonid species was suspended. The last national restocking program, using the eyed ova of brown and rainbow trout within southern Chile's rivers, was conducted from 1981-1982.

The first stock of Chinook-eyed eggs was introduced for farming in 1982, and the first stock of Atlantic salmon eggs was introduced in 1983. The growing of rainbow trout in sea cages commenced in 1987. By 1992, salmonid production had reached 58,000 t, and since that date, Chile has become the world's second-largest producer of sea-reared salmon.

The salmonid production carried out in southern Chile is spread across three regions, where 1359 concessions/designated rearing areas have been granted, 503 in the Los Lagos Region, 724 in Aysén Region, and 133 in Magallanes Region (Figs. 1-2), reaching a peak level of 1,043,144 t in 2020. In 2021, salmonid production reached 978,274 t, comprising 74.9% Atlantic salmon, 19.3% coho salmon, and 5.8% rainbow trout (Fig. 3), distributed across 354 concessions. In these areas, 35.3% of the total salmon production was produced in the Los Lagos Region, 49.3% in the Aysén Region, 15.1% in the Magallanes Region, and the remaining 0.3% in other regions (National Fisheries and Aquaculture Service; SERNAPESCA by its Spanisc acronym).

Chinook salmon, the species with the lowest farmed production, has managed to adapt and establish self-reproducing populations in southern Chile rivers, unlike coho and Atlantic salmon. The first run of wild spawning stocks Chinook was recorded from the Palena River in 1985 (Bravo et al. 2019). Although the production of farmed Chinook salmon has been significantly lower than the other domesticated species of salmonids grown in Chilean farms (Fig. 3), the naturalized populations of Chinook salmon are to be found between 39 and 53°S in Chile (Correa & Gross 2008) and between 43 and 54°S in Argentina (Di Prinzio & Pascual 2008).

Despite determined attempts to establish self-reproducing populations of coho and Atlantic salmon species for recreational fishing purposes, Atlantic salmon have not to date become established in Chilean watersheds (Soto et al. 2001, 2006, Arismendi et al. 2014, Bravo et al. 2019). In contrast, there is increasing evidence of naturalized coho salmon populations in the Magallanes Region. Mature individuals have been recorded returning to the rivers in Los Lagos Region (51°S), and there is evidence that these coho stocks have successfully spawned in the wild (Niklistcheck et al. 2013). An analogous situation has been recorded by

Maldonado-Márquez et al. (2020) in the Magallanes Region (55°S). Additionally, coho salmon juveniles have been recorded from rivers in the regions of Aysén and Magallanes (Górski et al. 2017, Chalde et al. 2019, Maldonado-Márquez et al. 2020).

The escape of farmed salmon is considered one of the main environmental threats in Chile. Since 2004, the salmon industry must report to the Chilean Authorities (SERNAPESCA) all escape events, including the size and number of escaped fish and the estimated cause of the escape (D.S. N°320, SUBPESCA 2001). Before that date, there is bulk information available for 1993-1996, when 4,843,700 fish were reported to have escaped from marine aquaculture facilities. Of this total, 40.2% were Atlantic salmon, 42.3% were coho salmon, and 17.5% were rainbow trout (Sepúlveda et al. 2013). No official records exist for the number of salmonid escapees from 1997-2003. However, of the total salmonids produced in 1996 (199,085 t), 38.8% comprised Atlantic salmon; 33.7% coho salmon; 27.3% rainbow trout, and the remainder, 0.2%, were Chinook salmon; which corresponds to the percentage of escaped salmonid species listed above for 1993-1996.

The General Law on Fisheries and Aquaculture (LGPA, by its Spanish acronym) in Chile states that, in the case of an escape of fish reared in an aquaculture facility, it is presumed that there will be environmental damage if the owner of the site fails to recapture at least 10% of the escapees, within 30 days from when the escape occurred (Article 118 quarter, Under Secretariat of Fisheries and Aquaculture; SUBPESCA by its Spanish acronym). In addition, the Environmental Regulations for Aquaculture (RAMA, by its Spanish acronym) states that "every salmon farm must have a contingency action plan, which establishes the actions and operational responsibilities in the event of circumstances likely to cause negative or adverse environmental effects" (D.S. N°320; SUBPESCA 2001). The authorities that regulate the escape of fish in Chile are the SUBPESCA, SERNAPESCA, and the Under-Secretariat of the Environment (SMA, by its Spanish acronym), which make up the Inter-Institutional Committee on Environmental Contingencies (CIICA, by its Spanish acronym).

In Chile, in 2020, a regulation established a "methodology for collecting information, processing and calculating the engineering requirements and technical specifications of cultivation structures" (R. Ex. N°1821; SUBPESCA 2020). The materials and structures used in the cages and anchorages must comply with these regulations to minimize the escape

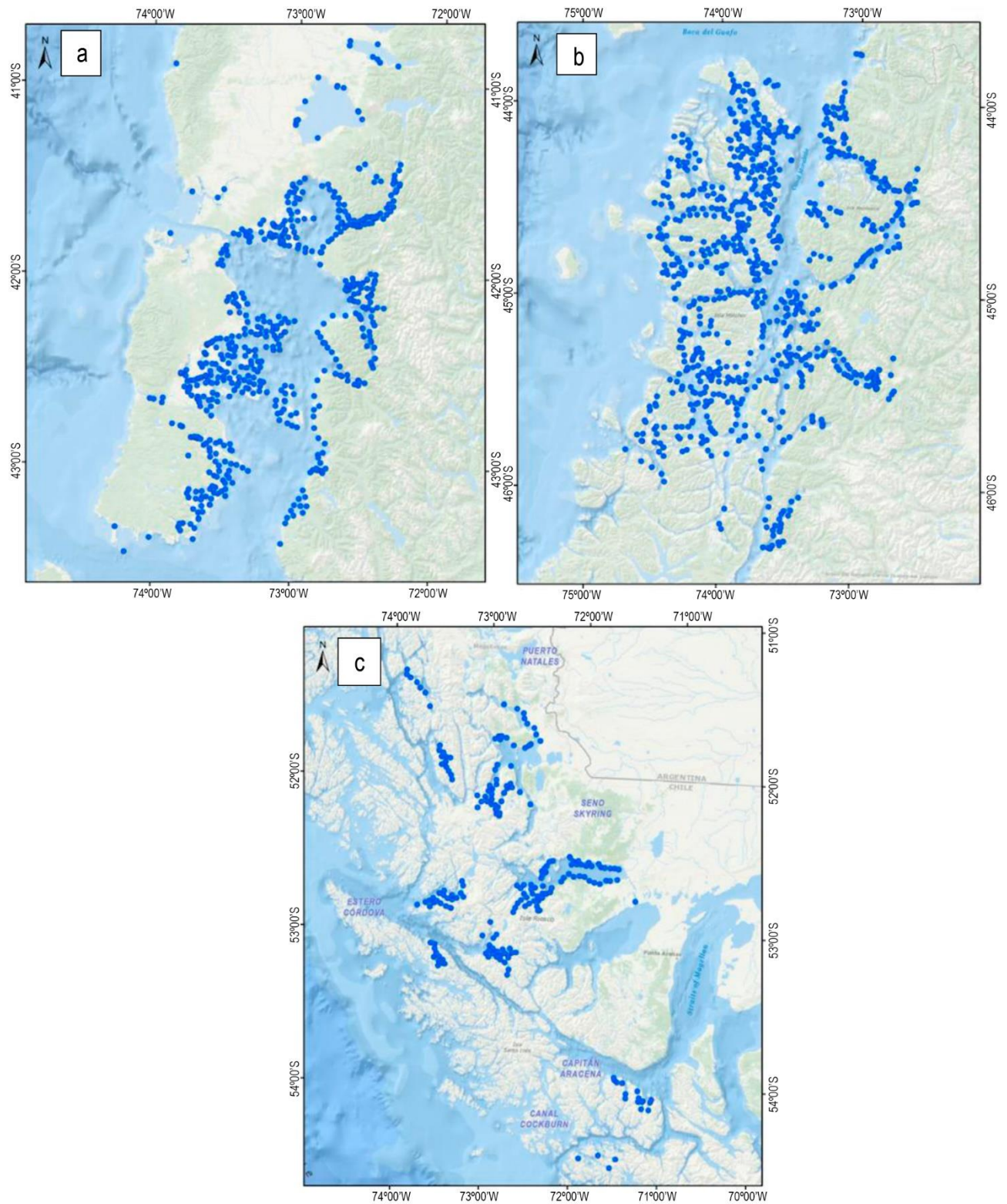


Figure 2. Map showing the locations of salmon farms in southern Chile, where salmon rearing is carried out. a) Los Lagos Region; b) Aysén Region; c) Magallanes Region. Source: SERNAPESCA.

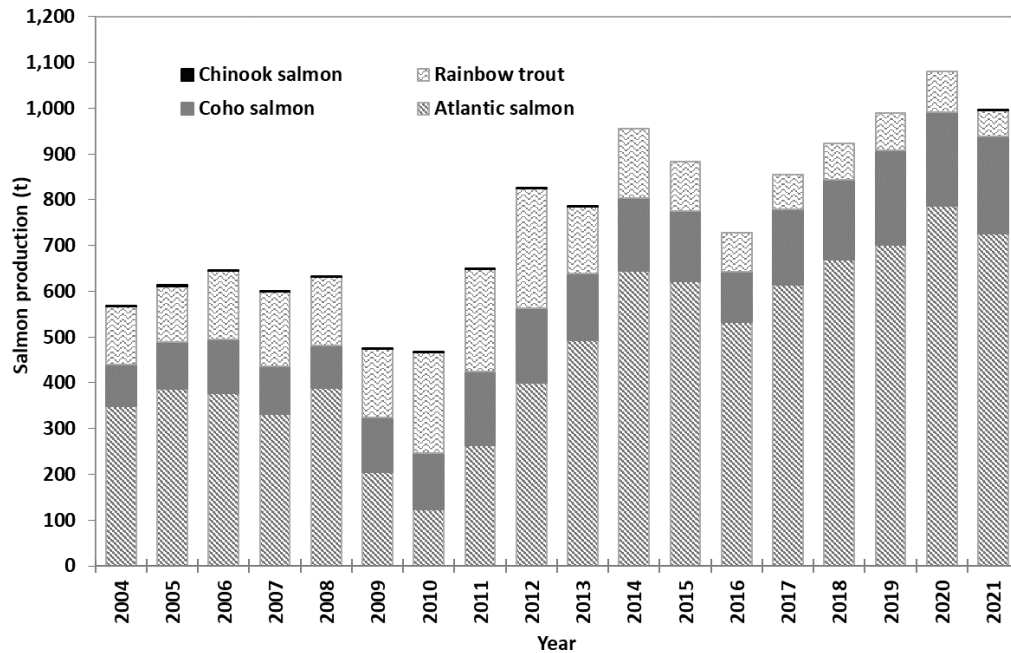


Figure 3. Salmon production in Chile (t) per year and by salmonid species. Source: supplemented with data supplied by SERNAPESCA.

of farmed fish. These regulations are equivalent to the regulations in Norway where, in 2004, the authorities defined the technical standards (NS 9415) that must be met by salmon farms at sea (Standard Norway 2009, Moe & Thorvaldsen 2021). In addition, guidelines that define the actions that must be taken following a fish escape was also published in 2020 (SERNAPESCA 2020). Finally, in January 2023, after four years of discussion, modifications were made to the LGPA, to tighten the regulations governing salmonid escapes (Regulation N°21532).

MATERIALS AND METHODS

The authors sought statistical data from the fisheries authority, SERNAPESCA, to estimate the number of escaped salmonids in Chile from 2004-2021. The database was requested by SERNAPESCA under Freedom of Information Legislation (transparency law) and was classified according to the salmonid species involved in the escape (Atlantic salmon *Salmo salar*, coho salmon *Oncorhynchus kisutch*, rainbow trout *O. mykiss*); the region where the escape occurred; the water body where the escape occurred (seawater, freshwater); the cause of the escape and the number of fishes recaptured after an escape incident. These data did not include Chinook salmon, as no escapes of this species were recorded over the study.

Farmed salmonids are reared in seawater in the Los Lagos Region, the Aysén Region, and the Magallanes Region (Fig. 1). However, escapes have also been reported from freshwater net-cage facilities in Los Ríos Region. Following the outbreak of the ISA virus in Chile (2007), only coho salmon and rainbow trout juveniles can be reared in net cages in lakes and rivers.

This study analyzed data covering 2004-2014 and 2015-2021. Data on the number of recaptures following an escape were included for 2010-2021, as these data were only available from 2010. Following the introduction of new regulations in 2015, SERNAPESCA requires that all escapes are documented, including the cause(s) of the escape. Therefore, the analysis relating to the causes of the escapes was carried out for two periods, 2004-2014 and 2015-2021.

In order to standardize the principal causes of escapes from farms, the authors used the classification proposed by Jensen et al. (2010) and Moe & Thorvaldsen (2021): that is, unknown; climatic; structural; rupture of the net-cage; operational; predation and inconclusive (without a clear cause). The analysis relating to the causes of the escapes was carried out for two periods, 2004-2014 and 2015-2021.

The yearly percentage of escaped salmonids, based on the total number fish reared each year, was determined by assuming that, at the time of harvest, the average weight of Atlantic salmon was 5.0 kg and for

coho salmon and rainbow trout was 3.0 kg. In the view of the authors, this is more realistic than the average weights of 4.5 kg for Atlantic salmon and 2.9 kg for coho salmon / rainbow trout, established by the Chilean authority (Res. N°1871; SUBPESCA 2022).

RESULTS

The recorded number of escaped salmonids

From 2004-2021, 109 escape incidents were recorded in Chile, representing around 8.53 million escaped salmonids. Of this total, 5.73 million were Atlantic salmon (67.2%), 0.83 million coho salmon (9.8%), and 1.96 million rainbow trout (23.0%). The number of salmonids that escaped annually by species in 2004-2021 and the number of escape incidents are shown (Fig. 4). The highest number of escapee salmonids were Atlantic salmon. No records of Chinook salmon escapes were found over this period. The highest number of salmonid escapes was recorded in 2013 (16 events). That year, the highest number of escaped farmed salmonids was recorded (1,653,763), comprising 98% Atlantic salmon and 2% rainbow trout.

Figure 5 shows the number of salmonid escapes, by species, per year relative to the yearly salmonid production over the period 2004-2021. Atlantic salmon (Fig. 5a) showed the highest number of escape incidents. The largest escape of this species occurred in 2013, caused by a major flood event in the Aysén Region. Coho salmon (Fig. 5b) showed the lowest number of escaped fish over the period. The highest number of escapees recorded in 2008 was 306,000 fish. For rainbow trout (Fig. 5c), the largest escape occurred in 2015 in net cages in Llanquihue Lake. This escape followed the eruption of the Calbuco volcano.

The largest number of escaped salmonids (70.1%) was recorded in Los Lagos Region, followed by the Aysén Region with 23% of the recorded escapes, where the highest number of escaped salmonids was recorded in 2013 and 2016 (Fig. 6). In the Magallanes Region, 4.6% of the total salmonid escapes were recorded. In Los Ríos Region, where only juvenile salmonid production is carried out, 2.3% of the salmonid escapes were recorded. The only escape incident reported by the Chilean salmon industry in Chile in 2021 occurred in a salmon farm rearing Atlantic salmon in the Magallanes Region (Fig. 6).

Causes of escape registered in the Chilean salmon industry

This study has shown that the loss of salmonids from rearing facilities in Chile has primarily occurred from

sea-based salmonid farms. There are also records of escapes, of a smaller magnitude, in freshwater (Fig. 7). In total, 80.5% of the escapes were recorded from seawater facilities. In comparison, freshwater units accounted for 19.5% of the recorded escapes. Some 80% of the escapes were recorded in farms using steel cages, and 20% were recorded from polyethylene cages; these percentages correspond to the relative proportions of cage types used by the salmon industry in Chile. In 2004-2021, the highest number of escapes from marine-based facilities were in March, July, and August, which correspond to the autumn and winter seasons, when weather conditions are more often difficult and challenging (Fig. 8).

The highest percentage of salmon escapees in seawater was recorded in 2008 and 2013, corresponding to 1.55 and 1.71% of harvested salmonids each year, respectively. In 2008, 0.99% of the escape corresponded to coho salmon and 0.56% to Atlantic salmon, while in 2013, 1.64% corresponded to Atlantic salmon and 0.07% to rainbow trout (Fig. 9).

Since 2015, the Chilean authorities have required each aquaculture operator to declare each escape's cause(s). Over the period 2004-2014, 89.4% of escapes were classified as unknown, 4.5% due to climatic conditions, 4.5% as structural defects, and 1.5% as rupture of the netting (Fig. 10a).

In the period 2015-2021, when the Chilean authority demanded that all escapes be documented, 11.6% of the events were classified as unknown; 18.6% as climatic conditions; 7.0% as structural defects; 39.5% as rupture of netting; 14.0% as operational; 4.7% as predation incidents, and 4.7% as inconclusive (Fig. 10b).

The escapes caused by 'rupture of netting' in 2015-2021 included two vandalism cases, resulting in the escape of 107,863 coho salmon. Escapes assigned to predation included two attacks by sea lions, which resulted in the escape of 14,267 fish. The highest escape level corresponded with adverse climatic events and resulted in the loss of 1,807,701 fish, rupture of netting permitted 484,994 fish to escape, and structural problems gave rise to an escape of 405,496 fish.

As outlined previously, according to the legal regulations before January 2023, it was mandatory to recapture at least 10% of the fish that escaped from a cage-rearing site. If an operator failed to reach this target, the company was considered to have breached environmental regulations and could be prosecuted. Figure 11 shows the number of salmon recovered following an escape incident from 2010-2021.

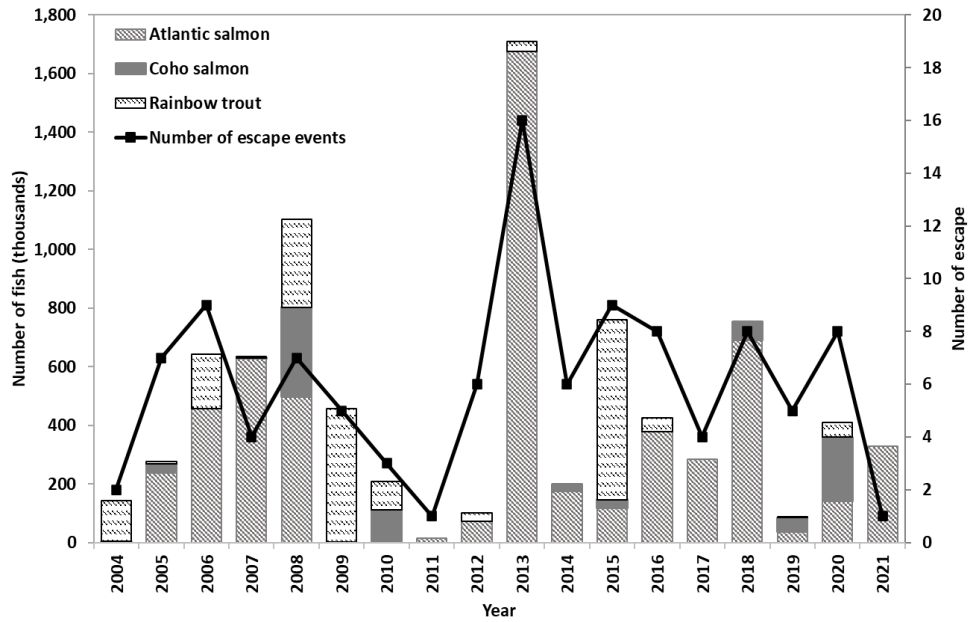


Figure 4. The number of recorded salmonid escapes per year and salmonid species vs. the number of escape events. Source: supplemented with data supplied by SERNAPESCA.

DISCUSSION

It is more than four decades since salmonids were reared for the first time in net cages at sea in Chile (1981). Initially, small wooden cages were used (7×7 m). These were built from local materials by the salmon farm workers, and the sites used were located in areas well-protected from excessive wind and currents. As salmon farming became more professional, the industry introduced far more sophisticated technology, with larger sea cages, and salmon farms were often located in more exposed areas. Locating the farms in such exposed sites greatly increases the risk of fish escaping from these structures. For example, in Los Lagos Region, the greatest percentages of escapes were recorded over the period 2004-2021 (70.1%). An additional factor here is the large tidal difference between low and high-water levels, reaching 7.3 m. In contrast, the tidal differences are just 3.2 m in the Aysén Region and 2.5 m in the Magallanes Region.

Although a technical standard (NS 9415) has been in operation in Norway since 2004, fish farm escapes are still one of the main problems affecting the Norwegian salmon farming industry (Glover et al. 2019, Holmen et al. 2021, Moe & Thorvaldsen 2021). From 2004-2021, 109 escapes were recorded in Chilean waters, and 8,531,000 farmed salmonids escaped. The highest percentage of salmon escapees in seawater was recorded in 2013, 1.71% of the total harvested population. A flood event in the Aysén Region occurred,

causing the escape of 1,296,607 Atlantic salmon, corresponding to 18.9% of the total escaped farmed salmon in 2004-2021 in seawater. In comparison, from 2010-2018, Norway reported 305 escapes involving 1,960,000 individuals (Moe & Thorvaldsen 2017). In contrast, once this regulation was implemented by the Chilean authorities in 2020, the number of escapes was greatly reduced, and in 2021 only one escape of 328,000 Atlantic salmon was recorded (Fig. 5a).

The reduction of salmon escapes may be explained by the high level of sanctions applied by the SMA. A substantial fine is imposed when the legally binding 10% recapture threshold is not reached, up to 5000 annual tax units (UTA, by its Spanish acronym), around USD 4,000,000 in 2022 values. In contrast, the fines imposed by the LGPA (Article 118 ter., SUBPESCA 1991) range between 500 and 3000 monthly tax units (UTM, by its Spanish acronym), equivalent to USD 38,000-226,000. In the latest modification of the LGPA regulations (Regulation N°21532), salmonid escapes will be punishable by a fine equivalent to the harvest value of the escapees that are not recaptured and by the suspension of the operator’s license for the site where the escape took place, for a period of between one and four years.

Most of the escapes reported from fish farms in Chile over the period 2004-2021 have been associated with structural defects, caused primarily by damage to cage structures (moorings, obsolescence of other equipment) and rupturing of net cages (Fig. 10), which

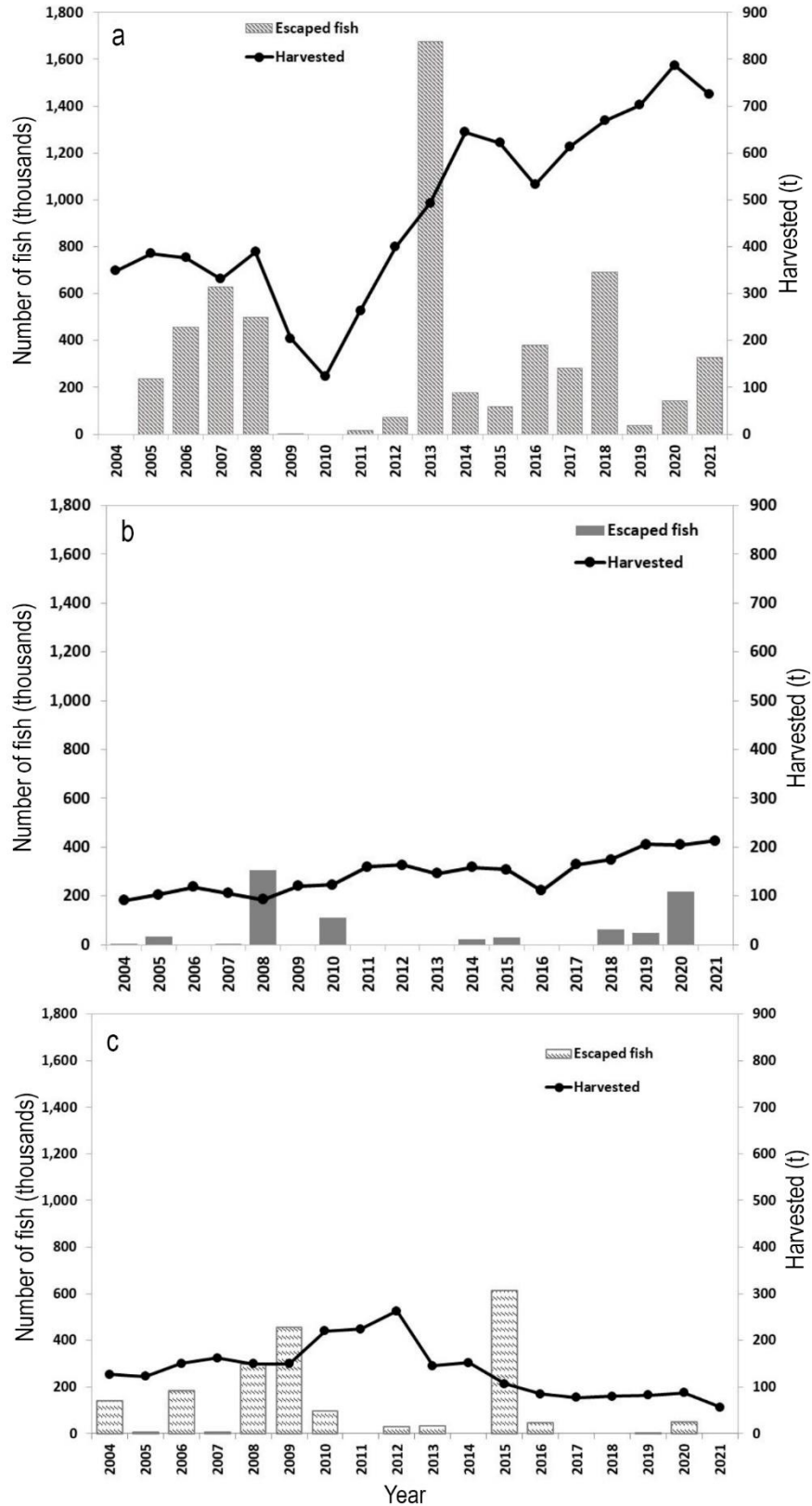


Figure 5. Number of salmon escapees per year and salmonid species. a) Atlantic salmon, b) coho salmon, c) rainbow trout. Source: supplemented with data supplied by SERNAPESCA.

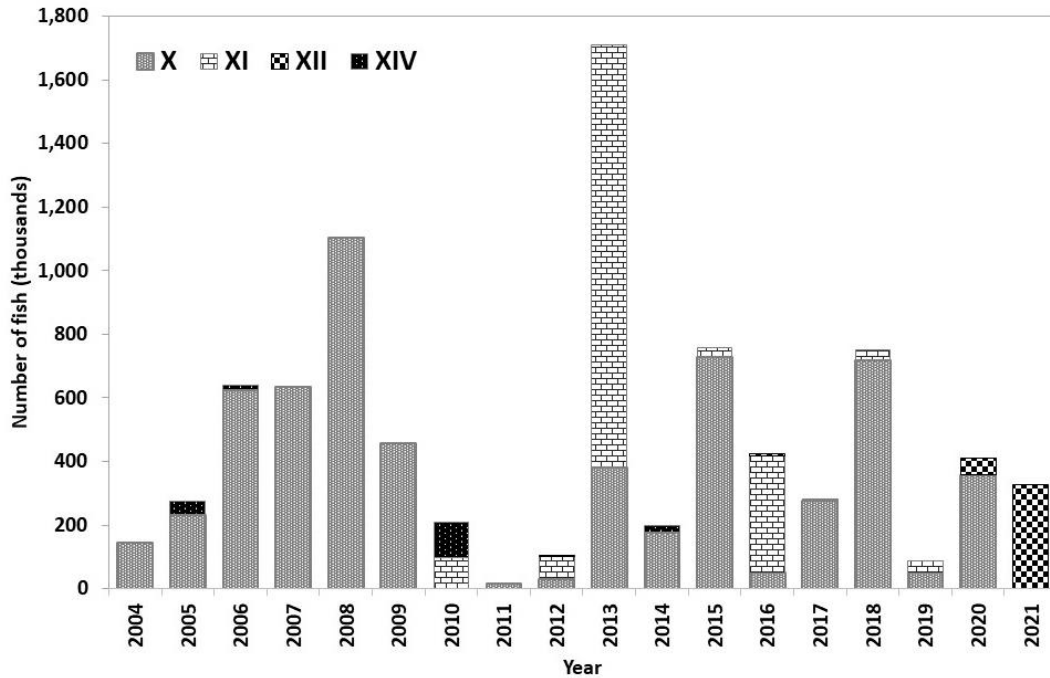


Figure 6. Number of salmon escapees per year and region of culture. X: Los Lagos Region, XI: Aysén Region, II: Magallanes Region, and XIV: Los Ríos Region. Source: supplemented with data supplied by SERNAPESCA.

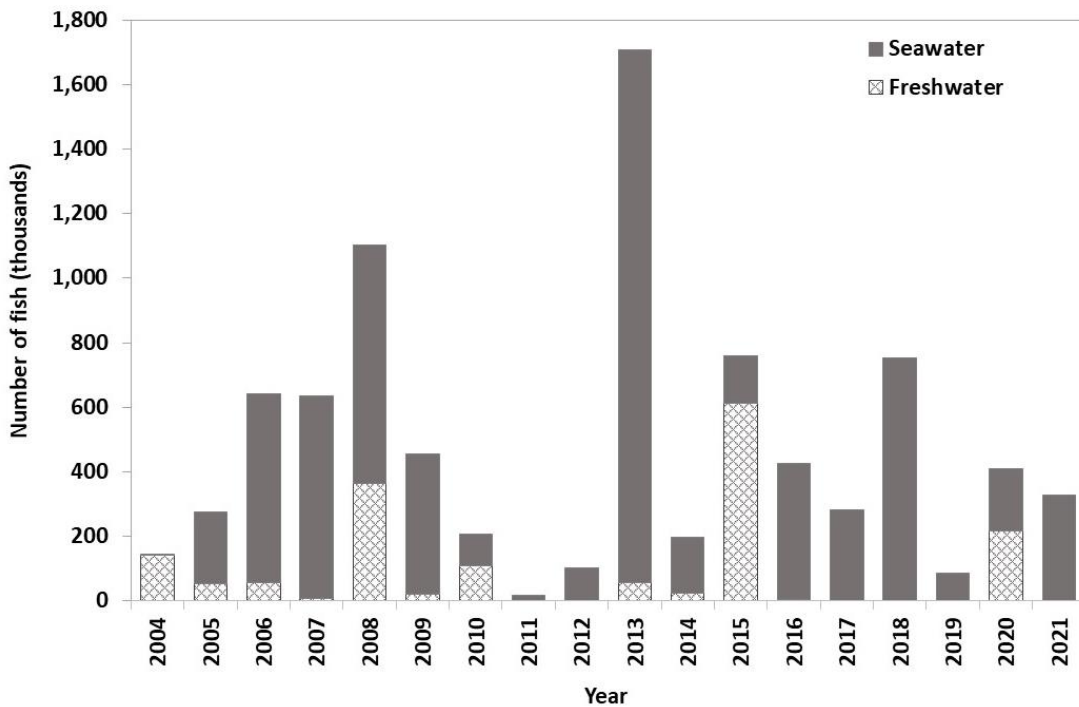


Figure 7. Number of salmon escapees per year in freshwater and seawater. Source: supplemented with data supplied by SERNAPESCA.

have collapsed due to adverse climatic conditions, such as severe storms. The situation is very similar in Norway, where most major escapes are associated with structural issues such as equipment failure (Jensen et al. 2010, Jackson et al. 2015, Moe & Thorvaldsen 2017).

Operational management (such as repositioning anchors and nets before delousing) has also been associated with an increased probability of escapes in other fish-farming countries (Jensen et al. 2010, Thorvaldsen et al. 2015, Moe & Thorvaldsen 2021).

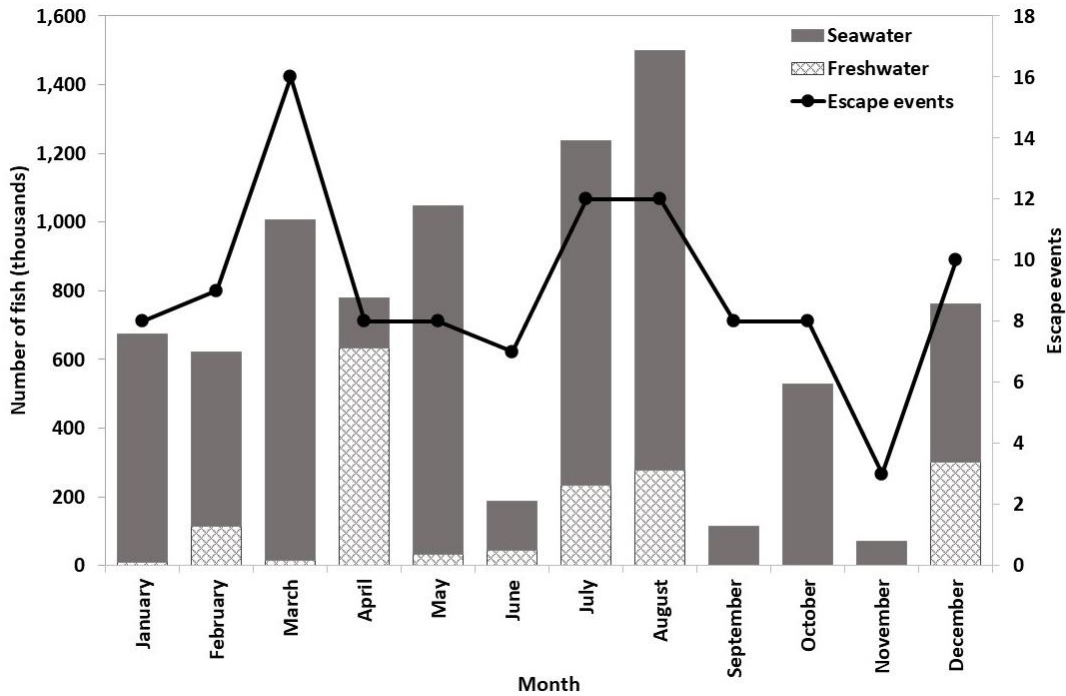


Figure 8. The number of escaped salmonids in freshwater and seawater and the number of escape events per month from 2004-2021. Source: supplemented with data supplied by SERNAPESCA.

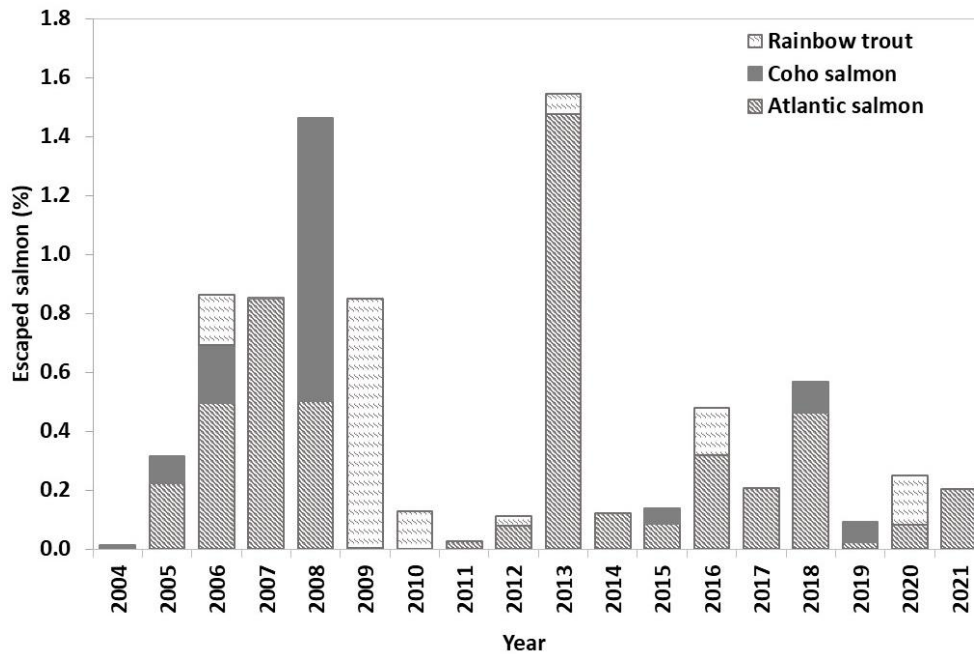


Figure 9. Percentage of recorded salmonid escapes per year and salmonid species concerning the total number of yearly harvests per species. Source: supplemented with data supplied by SERNAPESCA.

However, such issues have not been reported to the Chilean authority as causing the escape of farmed salmonids.

Environmental concerns generated by the escape of farmed salmon

The major concern with escapees in salmonid-producing countries in the northern hemisphere is the threat of genetic introgression due to interbreeding with

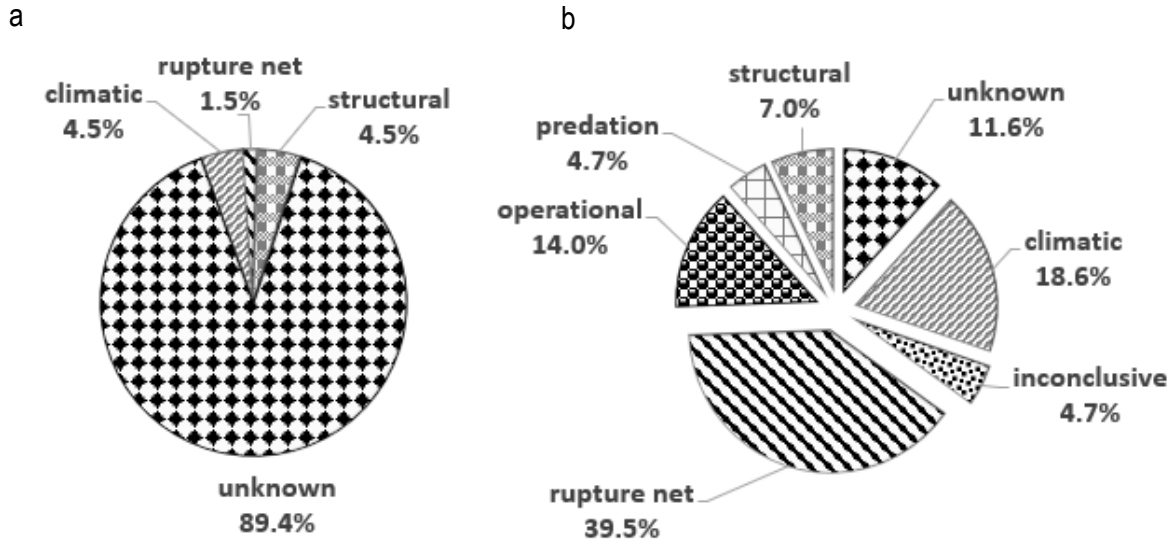


Figure 10. Percentages of different causes of salmonid escapes. a) 2004-2014; b) 2015-2021. Source: supplemented with data supplied by SERNAPESCA.

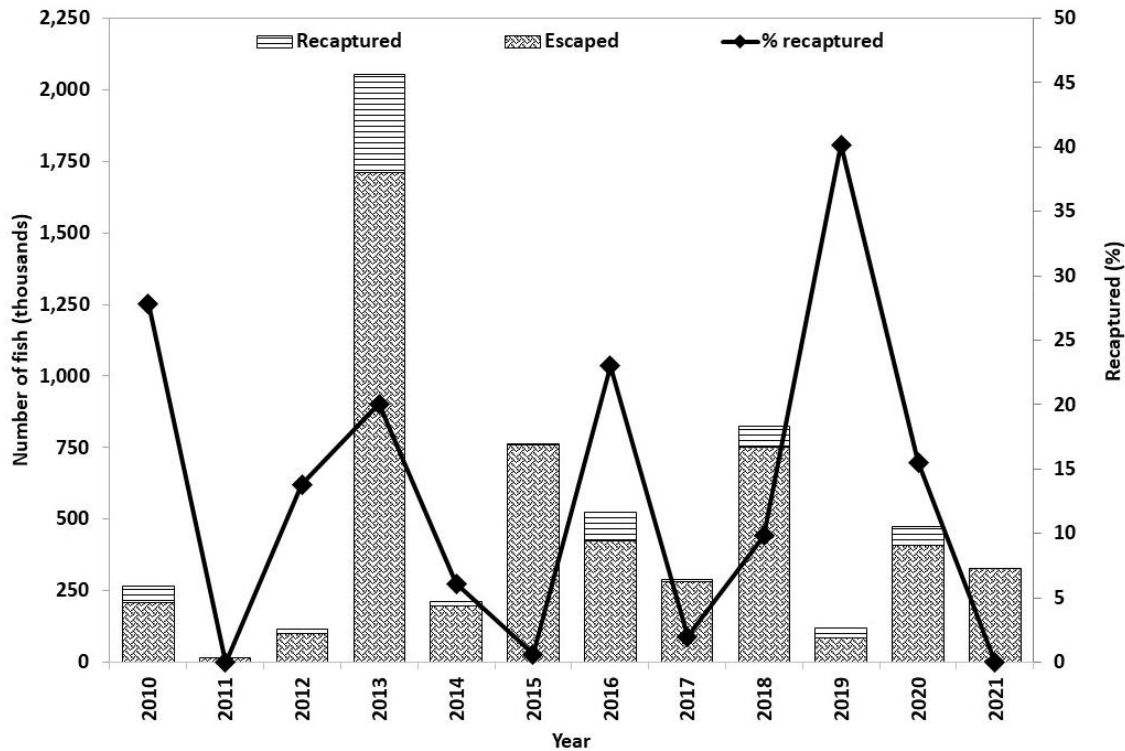


Figure 11. Salmonid escapes per year, and the number of fish recaptured in 2010-2021. Source: supplemented with data provided by SERNAPESCA.

wild Atlantic salmon (Gilbey et al. 2021, Moe & Thorvaldsen 2021). As a result of interbreeding with farmed escapees, significant genetic impacts on native Atlantic salmon populations have been reported in Ireland (Crozier 1993, 2000, Clifford et al. 1998a,b, McGinnity et al. 2003), North America (Bourret et al.

2011, Wringe et al. 2018, Sylvester et al. 2019), Norway (Karlsson et al. 2016, Bolstad et al. 2017, Forseth et al. 2017, Glover et al. 2017) and in Scotland (Coulson 2013, Gilbey et al. 2021). However, in Chile, all salmonids used for fish farming are non-native, exotic species. Although some species have established

self-reproducing populations in southern Chile, the risks of interbreeding between establishing strains and newly escaped, farmed populations have yet to be investigated.

The environmental concerns relating to farmed salmonids escapes have focused in Chile on their potential predatory effects on native fish, the effects related to the likelihood of farmed salmon establishing self-sustaining populations, and the transfer of pathogens and diseases to native fish stocks (Young et al. 2010, Arismendi et al. 2012, Niklitschek et al. 2013, Sepúlveda et al. 2013). Despite, at times, very large numbers of Atlantic salmon escaping into the wild in Chile, there is no evidence that these fish have established self-sustaining populations (Soto et al. 2001, 2006, Bravo et al. 2019). Soto et al. (2022) have reported that the risk of environmental impacts due to the escapes of farmed fish differs by salmonid species. It is lowest for farmed Atlantic salmon due to their low survival, lower ability to feed themselves following escape into the wild, and their lower reproductive capacity in the wild, compared to coho salmon and rainbow trout.

In contrast, Chinook salmon, the species least favored by the farming sector and the species demonstrating the lowest level of escapes into the wild, have established seemingly viable and strong reproductive populations in many basins of southern Chile and Argentina (Ciancio et al. 2005, Soto et al. 2007, Bravo et al. 2019, 2022). Both species, coho and Chinook, were used as the basis for ranching programs in the past, which may have played a role in their successful colonization of wild river watersheds. The colonization of rivers by coho salmon has only occurred relatively recently (Górski et al. 2017, Chalde et al. 2019, Maldonado-Márquez et al. 2020). Maldonado-Márquez et al. (2020) reported that the establishment of coho salmon at 55°S is due to escapes from salmon farms in the Aysén Region, at 51°S, the closet region in Chile where coho salmon are farmed.

Sea lions (*Otaria flavescens*) are a major predator of farm-reared salmonids and an important predator of escaped salmonids. Several researchers have reported that farmed Atlantic salmon do not survive successfully in the wild (Soto et al. 2001, 2006, Arismendi et al. 2009, Sepúlveda et al. 2013). A study (FIP 2004-24) commissioned by the SUBPESCA to evaluate the best methods of recapturing escaped salmon reported that Atlantic salmon remained in the vicinity of the cages for up to three days after an escape and that gillnetting was the best method to recapture these escaped fish (Melo et al. 2005). However, the recapture rate in this

study was only 3% of the total number of fish lost, which is far lower than the 10% threshold established by the authorities. Large salmonid escapes into the marine environment may attract a significant number of predatory sea lions, which in turn can harass and chase the salmon shoals, causing them to disperse more quickly, away from the vicinity of the cages, and obstructing the recapture of the escaped salmon.

There are no documented data on the number or percentage of escaped fish captured by sea lions. However, according to information published by Vilata et al. (2010), sea lions normally attack fish farm cages in the autumn and winter, reporting losses ranging from 2.62 to 8.25% of total production. This reduction in the attack by sea lions could be explained by improvement in the efficacy of the anti-sea lion nets used in the installations to protect the cages. Sea lions also cause very serious net damage, which can often result in the loss of fish from the cages. However, according to information supplied by SERNAPESCA, only two escape events caused by sea lions were reported in 2015.

It has been suggested that artisanal commercial fishing should be used to recover escaped fish in Chile (Soto et al. 2001). It has also been proposed that angling and recreational fisheries could control the overall numbers of escaped salmonids in rivers and lakes (Soto et al. 2006, 2007). According to the questionnaire results applied to artisanal fishermen, as a component of the project FIP 2004-24, only 32% of their declared gill net catch comprised fish that had escaped from fish farms near their fisheries. It was also noted that salmon farms regularly ask local commercial fishermen to help recapture escaped salmonids when an escape occurs. In the latest modification of the LGPA regulations, artisanal fishermen are authorized to catch escaped farmed salmonids. However, they must provide the authority with the number and species of farmed fish caught in their nets (Regulation N°21532).

There is no strong evidence that escaped salmonids have transferred either pathogens or diseases to native fish stocks in Chile. Salmonids are exotic, non-native species introduced from the northern hemisphere, and the main pathogens affecting salmonids in Chile were also imported with the eyed ova. However, since 2017, yearly studies have been carried out by the Instituto de Fomento Pesquero (IFOP) on wild fish in freshwater and the sea. In 2018 IFOP reported that *Piscirickettsia salmonis*, the most serious pathogen which infects farmed salmonid species in Chile, was only recorded in 38 of the 2160 wild fish analyzed (IFOP 2019). In contrast to countries in the northern hemisphere, where

escaped farmed salmon have been shown to act as reservoirs for the salmon louse *Lepeophtheirus salmonis* in coastal waters (Heuch & Mo 2001), the sea louse *Caligus rogercresseyi*, a natural parasite of wild marine fish in Chile (Carvajal et al. 1998), severely infests farmed Atlantic salmon and rainbow trout, while coho salmon have shown to be resistant to this species of louse (Bravo 2003, Pino-Marambio et al. 2007). There is no documented evidence in Chile of any negative effects of *C. rogercresseyi* infestation on wild marine fish populations. However, Marín et al. (2009) reported that, under experimental conditions and optimal salinity, *C. rogercresseyi*, copepodid stage, can successfully infect *Galaxia maculatus*, developing into the adult stage, mating, and producing eggs. This work confirms that *C. rogercresseyi* is non-host-specific, unlike *L. salmonis*, which only infests salmonids such as Atlantic salmon, sea-run brown trout, and sea-run char.

Besides the environmental concerns, large escapes of reared salmonids also increase the risk of economic and social losses. According to Naylor et al. (2005), the aquaculture industry bears the most direct cost in the form of foregone revenue, lost capital invested in grow-out stock, and public perception problems. Therefore, implementing strict regulations to minimize salmon escapes should benefit farming companies positively.

CONCLUSIONS

Salmon escapes in Chile from 2004-2021 were dominated by Atlantic salmon (67.2%), which constituted 74.9% of the total salmonid production in 2021. However, there is no evidence that this species has bred successfully in the wild or established self-reproducing populations, as has been the case with Chinook salmon, a species which is spreading widely across the rivers of southern Chile. In 2015-2021, 39.5% of the escapes resulted from the rupturing of net cages, mainly due to adverse climatic conditions. Over the years, regulations introduced by the Chilean authorities have been improved and strengthened to minimize the escape of farmed salmonids. In this way, just one escape event was reported in 2021, corresponding to 3.85% of the total number of escapees recorded between 2004 and 2021. The authors trust that the information compiled in this study will provide a more detailed understanding of the causes and impacts of farmed salmonid escapes in Chile.

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