Escaped farmed salmon and trout in Chile: incidence, impacts, and the need for an ecosystem view

ESCAPED FARMED SALMON AND TROUT IN CHILE: INCIDENCE, IMPACTS, AND THE NEED FOR AN ECOSYSTEM VIEW

Shortened title: Escaped farmed salmonids in chile

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ABSTRACT

The exponential growth of the salmonid farming industry during the last three decades has created conditions for massive escapes of these exotic species into natural environments in southern Chile. Here, we review and update information about salmonid escapes from 1993 to 2012 and examine their potential environmental, social, and economic consequences. We estimate that more than one million salmonids escape each year from marine farms, mainly due to weather conditions and technical and operational failures of net-pens. While a decrease in the magnitude of escaped Atlantic and coho salmon have occurred during the last several years, escaped rainbow trout have not followed the same pattern. Rainbow trout have become a greater threat to native ecosystems due to their greater potential to establish self-sustaining naturalized populations. The main ecological effects of escapees are related to short-term predatory effects upon native fish, long-term effects linked to the likelihood of farmed salmon establishing self-sustainable populations, and disease and pathogen transfer to native fauna. More research is needed to identify and develop reliable indicators to estimate the impact of escapees at the ecosystem level in both marine and freshwater systems. An understanding of the mechanisms of coexistence between native fishes and introduced non-native salmonids may be useful to design effective management strategies aimed at protecting native fish from salmonid introductions. A precautionary approach that encourages local artisanal and recreational fisheries to counteract colonization and naturalization of salmon species in southern Chile may constitute another management option.

Key words: fish farming, *Salmo salar***,** *Oncorhynchus kisutch***,** *Oncorhynchus mykiss,* exotic species, Chile

INTRODUCTION

Salmon and trout (hereafter salmonids) farming has experienced an exponential growth during recent decades, with Chile and Norway accounting for over 80% of the global salmonid aquaculture production (Figure 1; FAO 2011). In 2006 Chilean salmonid aquaculture reached its highest production, with nearly 640 thousands tons valued at US $3.8 billion (FAO 2011). This production corresponded mostly to Atlantic salmon *Salmo salar* (60.3%), coho salmon *Oncorhynchus kisutch* (17.5%), and rainbow trout *O. mykiss* (22.2%). Even though salmonids were initially introduced in the Southern Hemisphere for recreational purposes in the early 1900's (e.g. rainbow trout and brown trout *S. trutta*); additional introductions (mostly Pacific salmon species) occurred during the 1970's when they were farmed in hatcheries for ranching and aquaculture-fishery purposes (Basulto 2003). The expansion of the aquaculture industry in Chile started in the 1980's with salmonids grown to commercial size in net-pens in the inner seas and fjords of the Chiloe Archipelago in the Lakes Region (41-43^{o} S; Figure 2). Currently the aquaculture industry, both in size and number of farming facilities, is rapidly expanding further south (Aysen Region; 44-46^{o} S; Figure 2) (Buschmann et al. 2009, Niklitschek et al. 2013).

Salmonid farming phases mirror the cycles used by salmonids during their natural lives. Salmonids inhabit both fresh and marine waters, with freshwater systems playing a key role during early developmental stages. In Chile, the main growth of stocks takes place in the sea (Soto et al. 2001, Rojas & Wadsworth 2007) where they are reared in either square or circular floating net-pens until they attain commercial size (at 1-3 years of age). The current density of salmonids in each net-pen is 16-20 kg m^{-3}, although higher densities (~ 30 kg m^{-3}) were recorded in some facilities before 2008 (X. Rojas, *personal communication*). It has been shown that as the magnitude and number of sites where salmonid farming occurs increases, the potential consequences due to net-pen or farm failure increases, resulting in a higher probability of exotic escapees in the environment (Arismendi et al. 2009, Jensen et al. 2010, Niklitschek et al. 2013).

Here, we review and update information about salmonid escapes in Chile during the period of 1993 to 2012, and examine their potential environmental and economic consequences. We also provide a summary of the main factors that influence escapees, as well as discuss mitigation and prevention alternatives. We propose actions to diminish escape risks and highlight some management practices to mitigate negative impacts and enhance those which appear to be positive. This information is fundamental to understand the trade-off between the negative effects of biological invasions upon natural ecosystems and the high economic value of salmonids for aquaculture and recreational purposes in Chile and elsewhere.

CAUSES OF SALMONID ESCAPES

Several factors can explain the escapes of salmonids from facilities in coastal, marine and freshwater environments, including those of external and internal origins. Among these, external factors include attacks by predators (e.g. Sepúlveda & Oliva 2005, Vilata et al. 2010), theft or vandalism (intentional damage of nets to let salmon escape and then steal the fish), and adverse weather conditions, whereas internal factors are directly related to and under the responsibility of the fish farmer and include failure or neglect during routine fish handling procedures and site maintenance and accidental boat collisions (Sepúlveda et al. 2009). Reports by salmonid farm companies during the period 2004-2009 indicate that escape events were primarily caused by severe weather conditions (30%), theft (21%), and structural failure of net-pens and deficient handling incidents (18%; Figure 3). Storms lead to stronger waves and currents, resulting in ripping of the net-pen tethering ropes, breaking of the net-pen mesh, or tipping over of the net-pens (Jensen et al. 2010). Unfortunately, due to the high demand for new farming sites often the selection of a new location does not include proper consideration of potentially adverse environmental conditions (i.e. water currents, winds), increasing the risk of fish escapes during extreme adverse weather conditions. Overall, the causes of salmonid escapes are similar to those reported by producers in other salmonid-producing countries such as Norway, Canada, and Scotland (Valland 2005), but there the responsibility for fish escapes lies mainly with the farmer and/or providers of the equipment and services, including routine site maintenance and fish handling (Melo et al. 2005). Routine net-pen maintenance and fish handling procedures carried out at the farms also pose escape risks, from holes in the nets or transportation of fish among cages. Moreover, carelessness when changing fish or predator nets may result in the escape of fish. The sorting of fish into two or more net-pens through a tube can also lead to the involuntary release of species if the tube is poorly mounted. Moreover, collisions from boats used during operational activities, predator attacks (e.g. sea lions and birds), inadequate manufacturing materials and poor net maintenance increase the probability of escapes (Robles 2002). Lastly, although it is difficult to quantify, intentional damage of nets attributable to fishermen or farmers seeking to benefit from the subsequent captures of escaped salmonids or insurance policies are also factors that may increase escape risks.

QUANTIFYING SALMON AND TROUT ESCAPES

The real magnitude of salmonid escapes is most likely underestimated, mainly due to the fact that not all escapes are detected or reported. Number of escaped salmonids in Chile have been mostly reported or estimated after large and/or catastrophic events (Soto et al. 2001, Thorstad et al. 2008, Niklitschek et al. 2013). In addition to escapes from harsh weather conditions, farmed salmon may escape from marine net pens through persistent low-level leakage (Buschmann et al. 2009, Schröder & García de Leaniz 2011). Unfortunately, information on the number of salmonids that escape from regular leakages in Chile remains poorly documented. Soto et al. (2001) estimated that 1-5% of escapees come from leakages. However, this estimate has not been evaluated directly and remains somewhat speculative, being the threath of leakages insufficiently recognized (Sepúlveda et al. 2009).

By consulting insurance companies, Soto et al. (2001) reported an important number of escapes after major storms during 1994 and 1995 (Figure 4, Table S1). Since 2004, the salmon industry in Chile must inform government institutions about every escape event at their facility, but there are no official records of escapes available for the period 1997 to 2003. A total of 58 escape events were reported during the period 2004-2012 (Data from Soto et al. 1997 and from National Fisheries Service, Figure 4), accounting for almost 6.5 million salmonid escapees, although it is estimated that more than one million salmonids may escape each year in Chilean marine systems (Thorstad et al. 2008).

During the 13 yr of escape reports (1993 to 1996 and 2004 to 2012) a total of 3.7 million Atlantic salmon (289 600 yr^{-1}), 3.1 million coho salmon (239 954 yr^{-1}) and 4.0 million rainbow trout (313 892 yr^{-1}) were reported to have escaped from salmon farms located in both the Lakes and Aysen Regions. These amounts of escapes salmonids appear to be similar to those reported in other countries such as Norway and Scotland (440 000 yr^{-1} and 216 000 yr^{-1}, respectively; Thorstad et al. 2008, Jensen et al. 2010) and within a suggested range of escapes in Chile (1-2% of the total production, Niklitschek et al. 2006). However, if we consider the proportion of escaped fish from the total salmonids production, escaped fish in Chile duplicated those levels from Norway, and are similar to Scotland.

Overall, the number of salmon and trout reported to escape relative to the total production varies greatly among the three species analysed; it was lowest for Atlantic salmon and highest for coho salmon and rainbow trout: the average escape proportion 1993 to 1996 and 2004 to 2012 = (total no. escaped fish reported) / (production by species) were: 1.2 t^{-1} for Atlantic salmon, 2.4 t^{-1} for rainbow trout, and 2.5 t^{-1} for coho salmon. Comparing the two time periods (1993-1996 *vs*. 2004-2012) the escapes of Atlantic salmon and coho salmon decreased in the second period (Atlantic salmon: 374 349 to 251 933 yr^{-1}; coho salmon: 512 413 to 118 860 yr^{-1}) despite a marked increase in production during the second period, especially for Atlantic salmon. On the contrary, the escapes of rainbow trout increased during the second time period (211 669 to 359 324 yr^{-1}). This tendency in rainbow trout escapees is likely due to large-scale escape events in the Aysen Region during 2004, 2007 and 2008 years. The largest episode in 2004 corresponds to a specific event where about 1.8 million rainbow trout and coho salmon escaped due to bad weather conditions. The largest event in year 2007 was mainly associated to the tsunami that took place in April, where more than 1.5 million specimens were reported as escaped from net pens. However, Thorstad et al. (2008) refers to actual figures of about 5 million specimens, which could account for one of the largest escape episodes documented both at national and international levels.

In freshwater systems the information regarding salmon escapes is even more scarce, with a total of 11 events reported from 2004-2012 accounting for a total of 613 586 salmonid escapees, principally from lakes (75% rainbow trout and 25% Atlantic salmon). A positive and strong relationship between the magnitude of salmon production in freshwater facilities and the relative abundance of free-living salmonids including coho, Atlantic, rainbow trout, and Chinook salmon has been described in lakes of southern Chile (Arismendi et al. 2009, Young et al. 2009, 2010, García de Leaniz et al. 2010, Vanhaecke et al. 2012a). In fact, exotic salmonids have been reported as the most abundant fishes in freshwater systems of Chile (Soto et al. 2006). Since there is no documented evidence of successful natural reproduction of Atlantic and coho salmon in Chile, individuals from these species inhabiting freshwater systems appear to be exclusively originated from aquaculture escapes (Soto et al. 2001, Soto et al. 2006, Arismendi et al. 2009, Schröder & García de Leaniz 2011). Also, because no massive escape events have been reported in freshwater systems, the recurrent presence of salmonids in freshwater systems could be explained by frequent operational leakages from salmon farms.

ECOLOGICAL CONSEQUENCES OF ESCAPES

There is a general concensus among scientists that introduced species directly or indirectly alter the structure and diversity of natural ecosystems (Grosholz 2002, Naylor et al. 2005). Among freshwater introductions, salmonids are considered to be one of the most pervasive exotic species in the world (Pascual et al. 2009). In Chile, the environmental concerns from salmonid escapes have focused on short-term predatory effects upon native fish, long-term effects linked to the probability of farmed salmon in establishing self-sustainable populations, and disease transfer and pathogens (Young et al. 2010, Arismendi et al. 2012, Niklitschek et al. 2013).

Displacement of native fishes due to ecological interactions

Freshwater systems, including rivers and lakes, and marine systems have been invaded by salmonids and it is possible that their ecosystem-level processes may be affected through trophic cascade effects (Carpenter et al. 1996). Unfortunately, there is scarce information about the state of native fishes before salmonid introductions, which makes an understanding of their impacts more difficult to obtain (García de Leaniz et al. 2010). Based on stomach and stable isotope analyses, several studies conducted in Chile have shown negative effects from salmonid species on native fishes due to predatory and interference competition (Soto et al. 2001, 2006, Penaluna et al. 2009, Arismendi et al. 2009, 2012, Young et al. 2009, 2010, García de Leaniz et al. 2010). Collectively, the evidence suggests that salmonid species have detrimental impacts on native fishes in all types of ecosystems including lakes (Soto et al. 2006, Arismendi et al. 2009, García de Leaniz et al. 2010, Habit et al. 2010, Correa & Hendry 2012), rivers (Soto et al. 2006, Penaluna et al. 2009, Arismendi et al. 2012, Vanhaecke et al. 2012a,b), and inner seas (Soto et al. 2001). Lakes in particular, where most of the freshwater phase of salmonid aquaculture occurs, could be particularly sensitive to the impacts of escapes because top predator species may produce a detrimental impact to aquatic biodiversity and species richness (Moyle & Light 1996, García de Leaniz et al. 2010, Vanhaecke et al. 2012a,b). However, a more complete evaluation of the effects of predation and competition on native fauna is prevented by the fact that the basic biology and ecology of native aquatic communities in freshwater, inner seas, and fjords of southern Chile remains poorly understood.

Spreading of pathogens and diseases

Animal health, especially in response to disease, is another issue to consider when discussing the ecological impacts of salmonid escapes, because exotic salmonids can introduce new pathogens, alter disease patterns, and even act synergistically to increase the impact of other stressors (García de Leaniz et al. 2010, Habit et al. 2010). During the past few years, several aquaculture facilities have been affected by epidemic outbreaks of diseases, favored by the conditions of fish being confined at high densities and the short distance that separates farms (Asche et al. 2010). In addition, escaped salmonids can travel large distances (Melo et al. 2005, Whoriskey et al. 2006, Skilbrei et al. 2009), and hence they become potential vectors for parasites and diseases at a broad scale (Thorstad et al. 2008). Epidemiological studies conducted in the Northern Hemisphere (i.e. Ireland, Scotland, Norway, and Canada) suggest that the occurrence of diseases such as Rickettsial septicemia and sea lice (*Caligus* spp.) in both salmonids and native fishes are directly related to higher concentrations of farmed fishes (Krkosek et al. 2005, Naylor et al. 2005). Also, a virus that regularly affects salmon farms in different countries including Chile is the infectious pancreatic necrosis (IPN) virus, which has been detected in all salmon species at all developmental stages (freshwater and ocean phase of aquaculture) as well as in native fishes, molluscs and crustaceans (Rodríguez et al. 2003, Asche et al. 2010). The infectious salmon anemia (ISA) virus has also been documented in salmon farms in Norway, Canada, Scotland, United States, and recently in Chile, causing enormous damage to the industry and the local and national economy (Niklischek et al. 2013). In Chile, the potential transmission of diseases from farmed salmonids to other taxa such as marine birds and mammals is yet unknown. However, preliminary evidence of skin lesions in dolphins has suggested a potential link to the salmonid aquaculture industry (S. Heinrich, *personal communication*).

Threats of establishment from escaped salmonid populations

Rainbow trout and Chinook salmon escapees may pose the greatest threat to native ecosystems because they have naturalized populations compared to both Atlantic and coho salmon, thus the magnitude of their ecological impacts may increase when they can establish self-sustaining populations (Soto et al. 2006, 2007, Correa & Gross 2008, Arismendi et al. 2009, Arismendi et al. 2011a,b). The successful establishement of self-sustainable populations could be related to a relatively high plasticity of these species (i.e. ability to feed on a broad range of organisms; Becker et al. 2007). Coho, Chinook salmon and rainbow trout have also been part of ranching programs in the past which eventually may also played a role in their establishment, especially in the case of Chinook salmon (Astorga et al. 2008). It is also possible that salmonid escapees might increase the probability of establishing self-sustaining populations when those escapes are greater than from slow leakages or “silent” escapes (Consuegra et al. 2011). According to Consuegra et al. (2011), the invasion success may also depend on propagule pressure. For example, rainbow trout may have achieved high establishment sucess and expanded more rapidly than other anadromous species (such as brown trout) because its spread is aided by escapes from fish farms (Ciancio et al. 2008).

For Atlantic salmon there is no evidence for the establishment of naturalized populations (Soto et al. 2001, 2006, Schröder & García de Leaniz 2011). Indirect evidence suggests that this species fails to establish because escaped individuals do not feed or grow very well in the wild (Soto et al. 2001). This is similar to other systems where efforts to establish Atlantic salmon as a game fish species have failed (Naylor et al. 2005). Considering that Atlantic salmon have traditionally been the highest proportion of farmed salmonid in Chile, the risk of establishment is an ongoing, unresolved question. Similarly to Atlantic salmon there no evidence suggesting that coho salmon may successfully reproduce in the Aysén Region, although some evidence of reproductive individuals migrating upstream has been reported (Becker et al. 2007, Soto et al. 2007). Hence, the possibilities for management and mitigation in these species may be greater than for the other salmonids.

SOCIAL AND ECONOMIC EFFECTS OF ESCAPES

The conflict between the salmon industry and the artisanal fishing sector is one of the most relevant socio-economical impacts arising from salmon escapes in Chile. Small-scale fishing of escaped salmon could have an important social and economic effect, providing food security and extra income for rural people and low-income families (Arismendi 1997, Soto et al. 2001). For example, during the massive escapes of 1994-95 a large number of local fishers, often women and children, were fishing for salmonids (mostly with gillnets), which were then sold in local markets (Soto et al. 2001). The practice is still quite common in communities near salmon farming locations in the inland seas and lakes. It is important to note however that the application of large quantities of antibiotics in the salmon aquaculture in Chile has environmental implications that potentially impact the health of humans and wildlife (Fortt et al. 1997).

Currently salmonids are the property of farm owners even after they have escaped, so the capture and marketing of escaped salmon by artisanal fishermen is considered an illegal practice. During the previously mentioned massive escapes, fishermen created considerable turmoil requesting fishing rights over these escaped salmon, in addition to claiming that native fish resources were affected (Soto et al. 2001). The possibility of an artisanal fishery is somewhat feared by salmon farmers as legalization of a salmon fishery could generate competing products whose standards may not be at the level of those adopted by the farmers' organizations (Niklitcheck et al. 2013). It is clear however, that products from the salmon fishery could be oriented to local markets for domestic comsumption, whereas production from salmon aquaculture is aimed for export to international markets. However, for salmon farmers opening a fishery of escaped salmon could enhance vandalism and/or theft at the farms. If some of the escaped salmon species are indeed able to establish and develop naturalized populations, we predict a new "battleground" in the marine environment between artisanal fishery and salmon farming.

In addition, sport fishing entities are debating the pros and cons of this new species for tourism and business. Hence this creates conflict between those who want to fish and those who would like to eliminate these returning exotic salmon runs.

PREVENTION AND MITIGATION OF ESCAPED SALMONIDS

Preventing salmonid escapes

Considering that many escapes are due to human mistakes, preventive measures can be effective in a number of cases. A prevention system utilized in aquaculture facilities located in streams is the use of physical barriers to prevent fish from escaping. The barriers are strategically located in critical connection points throughout the facilities, such as pools or tanks containing the fish in water inlets and outflows. Some companies have more efficient systems that minimize the risk of escapes by using recirculation tanks. In these closed and independent systems, salmonids do not come into contact with the outside environment.

Ocean grow-out farms pose the largest challenges for the industry. Although anti-predator nets protect against external attacks and may also serve as containment when fish nets tear, there are no actual physical barriers in place. Instead, fish farmers have developed maintenance practices to prevent nets from breaking and releasing fish into the environment. The proper tension of fish and anti-predator nets through anchoring and mooring systems reduces friction between materials and prevents nets from sticking to one another, thereby preventing sea lions from approaching the fish. Other typical practices to reduce escape risks include replacing and maintaining nets and monitoring by divers or the use of video cameras.

Mitigating salmonid escapes

The aquaculture regulatory framework in Chile includes environmental regulations (the Environmental Impacts Assessment System, SEIA) established in 1997, and the executive decree on environmental norms for aquaculture (RAMA). These regulatory tools and their operational norms affect both licensing and operation of fish farms. The SEIA includes the establishment of contingency plans for escaped salmonids and, according to the RAMA, these plans must follow special guidelines. These guidelines have information about operational procedures and devices to recover escaped salmonids, as well as the obligation to provide immediate detailed information to authorities about escapees. Mandatory reporting of escape incidents was introduced to Chile in 2001, with a national statistics database since 2004. This has enabled a gross assessment of the overall status of the escape problem at an industry-wide scale from year to year, and an evaluation of the causes of escapes.

Different and non-exclusive techniques are used to capture free-living salmonids that have escaped from marine grow-out farms. The most popular technique is try to capture the escaped salmonids with nets or mobile empty cages, often using pellets to attract escaped salmonids to a particular location (Melo et al. 2005). All aquaculture staff is required to work following an escape event, but often the employees often do not have training in how to manage or respond to such events.

There is no quantitative information, however, on how effective these prevention techniques and recapture systems are. The background information collected in other producer countries reveals a low success rate for recapture efforts (recaptures amount to < 3 percent) (Thorstad et al. 2008). This is likely the case in Chile, because current recapture systems reflect mitigation measures taken by the industry which are both inefficient and insufficient (Melo et al. 2005). The RAMA does not detail specific mitigation and recapture protocols, and producers have to define their own action plan to deal with escaped fish. According to Melo et al. (2005), salmonids not only do not remain in the vicinity of the cages, but they can move up to 3 km in 10 hours, revealing high levels of mobility. In fact, molecular analyses on rainbow trout indicated that the incidence of escapees is widespread (Consuegra et al. 2011). When large-scale escape events often take place under bad weather conditions, time becomes a critical factor and recapture tasks are extremely complex, further reducing the success of such operations. Additionally, action plans are not always enforced due to the limited capacity of local and regional government institutions. An improved knowledge of pattern of movements, behavior and survival rates of escapees would be useful to inform natural resource managers and the fish farming industry.

To reinforce the action plans and also the fiscalization by the government institutions it would be useful to determine the specific origin of escaped salmon. Recently some tools have been developed to differenciate potentially escaped from free-living fish, including the detection of manganese concentration from scales (Adey et al. 2009) and stable isotopes of carbon and nitrogen (Schröder & García de Leaniz 2011). Furthermore, some approaches with molecular markers have been used in Chile to distinguish if salmonids in rivers and lakes are descended from specimens introduced for ranching or from individuals escaped from salmon farms (Astorga et al. 2008), or if a genetic admixture occurs between individuals escaping from fish farms and "naturalized" salmonids (Consuegra et al. 2011). Using this approach as a baseline, in the future it might be possible for each aquaculture facility to have a unique and registered genetic marker stored in a database, allowing a posterior cross-comparison with escaped fish and thus allow determining their specific origin.

Soto et al. (2001) proposed that a mitigation procedure could be that artisanal fishers try to control escaped salmonids by capturing escapees, especially considering that artisanal fishing commonly occurs around fish farm locations. In addition, there is potential for developing a recreational fishery especially following an escape (Arismendi & Nahuelhual 2007). Such fish could be allowed in a take quota (assuming that the fish are safe to eat), complementing the current catch and release approach for trout. Sport fishing could be improved and facilitated around farms to collect and control escaped fish and to provide additional income to local people and fishermen. It is clear that such a fishery must be well-organized to be sure it does not conflict with the industry and/or facilitate more escapes. The promotion of both artisanal and recreational fisheries should be considered only as a mitigation procedure. Although all species of salmonids introduced for aquaculture purposes are already are present in both freshwater and marine environments, some of them are not yet reproducing on their own (Soto et al. 2001; Soto et al. 2006; Arismendi et al. 2009). The removal of these potential new invasive species through a salmonid-based fishery could certainly decrease the likelihood of new establishments. Artisanal fisheries based on salmonids should be of limited access and highly regulated in order to discourage the promotion of further releases.

It is important to have into consideration that artisanal and recreational fisheries should not impact native species. Fortunately, in freshwater systems of southern Chile there are no native fish that could be potentially affected by artisanal or recreational fisheries. Native fish are smaller in size than salmonids, and thus they have a low potential for incidental capture. In general, salmonid-based artisanal fisheries use gillnets, which are highly size-selective. Anglers tend to use a catch-release approach, avoiding negative effects on native fish. In marine environments however, the potential for incidental capture of native species is greater than in freshwater, but these native fish already have prexisting historical fisheries and thus an established commercial value (Soto et al. 2001).

Local and regional natural resource managers should be involved to assess free-living and self-sustaining salmonid populations, and should begin discussions with interest groups on the use and management of such populations. To inform these managers, investigators need to evaluate social and economic scenarios involving these potential fisheries. If a monetary value is given to these escaped salmonids then the industry could be held accountable to compensate the local and regional governments.

RESEARCH NEEDS

As has been identified in this review, there are still several gaps in the knowledge of the impacts and consequences of escaped salmonids in Chile. Thus, considering that salmonid aquaculture is expected to continue to grow, different research needs should be identified including biological, social and economic aspects that could generate useful information for decision makers. One of the most important research needs is to implement a monitoring program to evaluate the abundance and impacts of escaped salmonids. For example, to establish long-term field surveys to estimate the relative importance of fish escaped from the native fishes and and naturalized populations (see for estuarine areas Soto et al. 2001; for lakes Arismendi et al. 2009, 2011; and for streams Soto et al. 2006, 2007). It is also important to evaluate and develop reliable indicators to estimate their impact on native species and ecosystems, as well as their social and economic impact in both marine and freshwater ecosystems (Velásquez et al. 2011). For example, to test broad scale hypothesis about taxonomic homogenization and expansion of introduced species a paired comparison between historical and current presence/absence of both native and introduced species appears to be a useful tool (Marr et al. 2010, 2013).

While additional work is needed to increase our knowledge of the processes underlying the patterns described in this review, more data could improve management of non-native salmonids in areas where they impact native fishes negatively. For example, patterns of apparent coexistence of non-native trout and native fishes in some streams could provide clues for managing invasions in more heavily impacted streams (see conservation status in Campos et al. 1998, Habit et al. 2006). Thus, understanding mechanisms of coexistence between native fishes and introduced non-native salmonids may help in designing effective management strategies that protect both native fishes and important recreational fisheries. Coexistence may also improve our knowledge of the functioning of pelagic and benthic communities in lakes and inner seas of southern Chile, maintaining areas without salmonid farming as reference sites to understand more completely the effects of free-ranging salmonids. Even more important is to monitor lakes without salmon farming, especially lakes without trout which seem to be very scarce (Soto et al. 2006, Correa & Hendry 2012).

CONCLUSIONS

Aquaculture is continuing to grow and expand worldwide and so is salmonid farming probably everywhere including the major producing countries such as Norway and Chile. Effects of escaped salmonids in regions where they are not native are quite different from where they are native such as Norway, because there major impacts are related to genetic modification of natural populations for Atlantic salmon (Fleming et al. 2000, Thorstad et al. 2008). In Chile the effects are mostly related to direct impacts of escaped individuals on native fishes and the local environment, including important social and economic effects related to artisanal and recreational fisheries. The establishment of new salmonid species such as Atlantic and coho salmon, with their potential long-term effects due to naturalized populations, requires urgent action by decision makers.

In such a complex situation, with ecological, social, health-related, political and economic implications, all stakeholders must assume their responsibilities. Government agencies must ensure the ecological balance of water systems, minimum escape levels and effective mitigation measures, including regulations to help manage these values. Salmonid farmers must undertake a more proactive prevention role, including: (1) identify critical issues in every stage of salmon farming, so as to establish protocols to prevent salmon escapes; (2) conduct an adequate selection of fish farm sites; (3) design optimal structures for the area's oceanographic conditions; (4) develop and implement special technologies and materials to prevent escapes; and (5) prepare more effective procedures and guidelines for the recapture of escaped fish. In this context, the coupling of aquaculture with fisheries (artisanal and recreational) could help manage the natural resources which both of these activities require, and thus the management of escaped salmonids should be addressed accordingly.

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FIGURE CAPTIONS

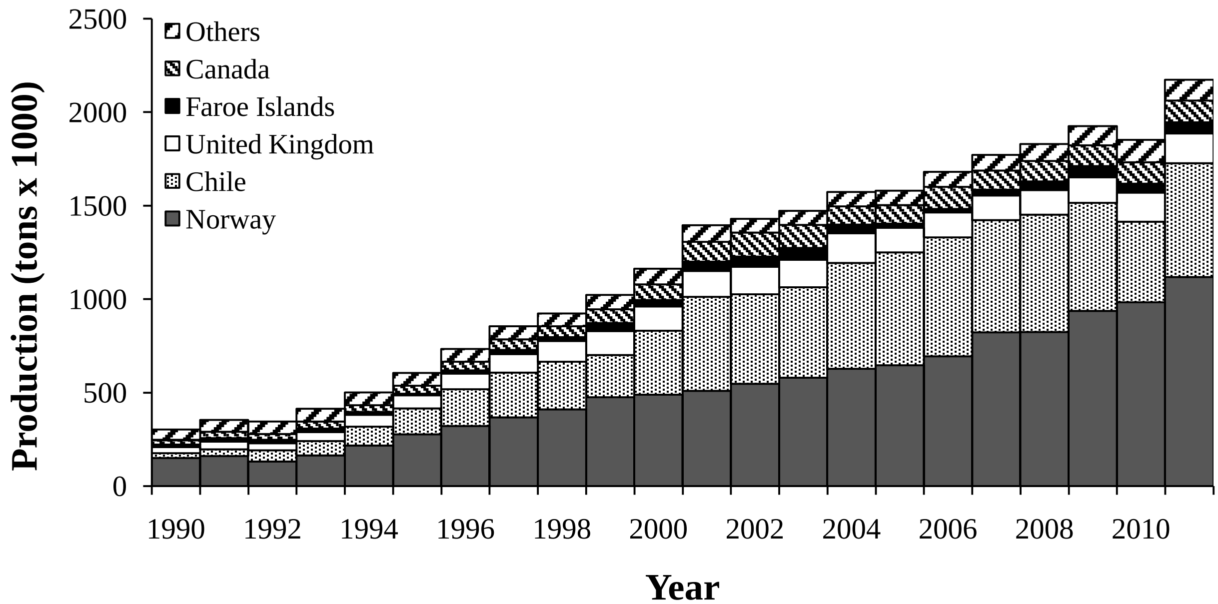
Figure 1. World production (thousands of tons) of salmonid species including rainbow trout, coho and Atlantic salmon between 1990 and 2010 (main producers are shown). Source: FAO aquaculture statistics.

Figure 2. Salmonid farm locations in the Lakes and Aysen Regions.

Figure 3. The main technical issues associated with salmonid escapes, according to reports by salmonid farm companies in (a) the Lakes (filled bar) and (b) Aysen (open bars) Regions. Source: National Fisheries Services and Chilean Navy.

Figure 4. Total salmonid production and reported escapes. Escape data for 1993-1996 from Soto et al. (1997) and for 2004-2012 from National Fisheries Service (unpublished information). Production data for 1993-2012 from Fishing Statistical Yearbooks.

Figure 1



Others
Canada
Faroe Islands
United Kingdom
Chile
Norway
Production (tons x 1000)
2500
2000
1500
1000
500
0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year

Figure 2

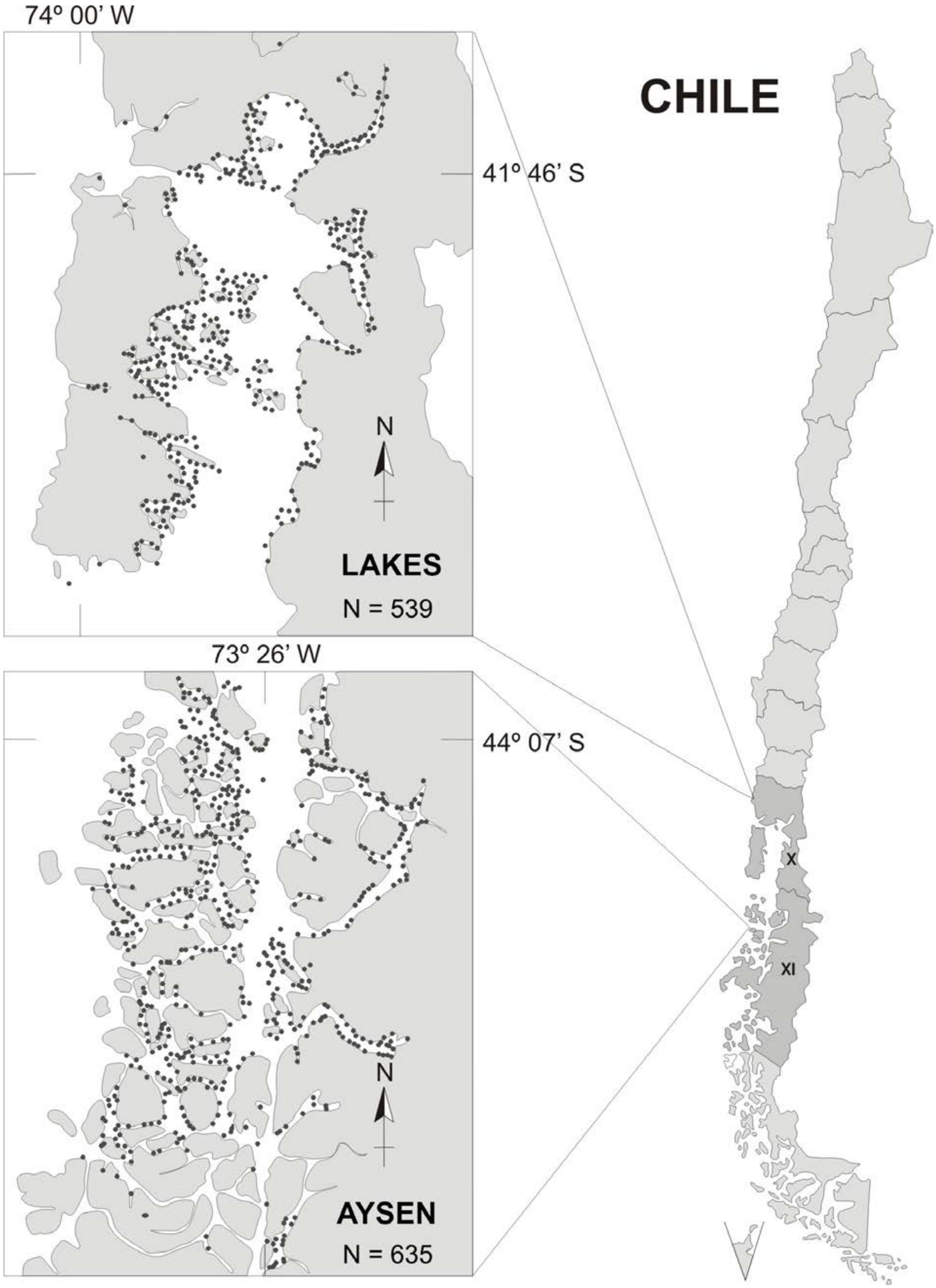

74º 00' W
41º 46' S
N
LAKES
N = 539
73º 26' W
44º 07' S
N
AYSEN
N = 635
CHILE
X
XI

Figure 3

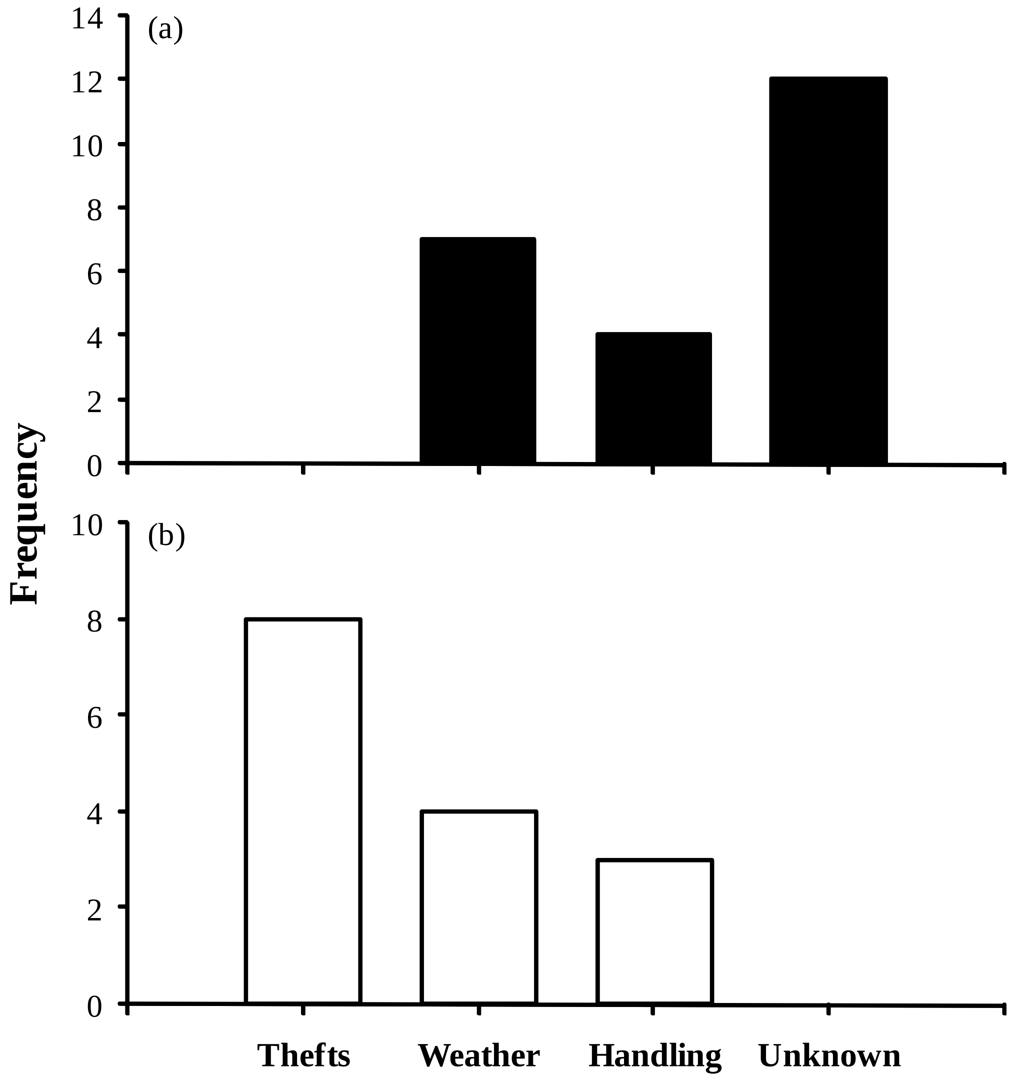
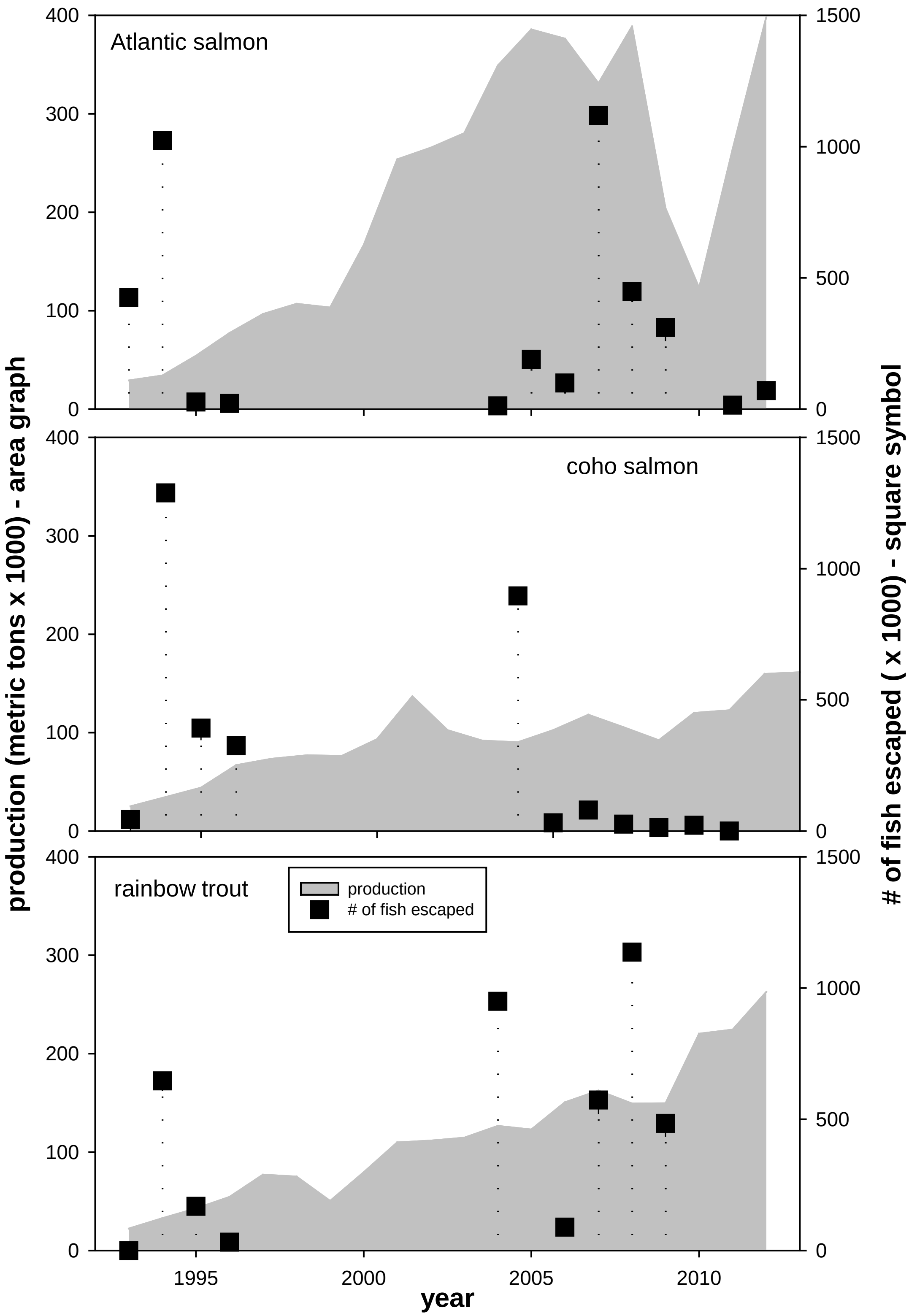

(a)
(b)
Frequency
0
2
4
6
8
10
12
14
Thefts
Weather
Handling
Unknown

Figure 4


Atlantic salmon
coho salmon
rainbow trout
production
# of fish escaped
production (metric tons x 1000) - area graph
# of fish escaped (x 1000) - square symbol
year
0
100
200
300
400
500
1000
1500
1995
2000
2005
2010