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REVIEW

REVIEWS IN Aquaculture

Environmental risk assessment of non-native salmonid escapes from net pens in the Chilean Patagonia

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Abstract

Here, we review extensive information to estimate environmental risks from escaped non-native salmonids based on the assessments of *hazard*, *sensitivity* and *exposure* of discrete water bodies in Chile. In 2020, the country harvested about 1 million tons salmonids from net pens located along 1500 km of highly biodiverse coastline. We base our analysis on existing scientific information and authors' expert opinions including an assessment of knowledge gaps and uncertainties. Risks of environmental impacts differed by salmon species, being lowest for Atlantic salmon due to its estimated lower survival, lower ability to feed after escaping and lower reproductive capacity in the wild compared to coho salmon and rainbow trout. Overall risks due to escapes of any of the species were highest in areas of both high farming intensity and low capacity of mitigating escapes (by wild predators and fishers) such as Aysén District. At same time, risk was higher in the most farmed areas that also presented suitable habitats to support reproduction and juvenile salmonid rearing. However, the risk estimation certainty differed among species being lowest for Atlantic salmon due to insufficient monitoring of their fate in the wild. Monitoring the fate and impacts of escaped salmonids, specially in higher risk areas is recommended to improve risk projections and to prevent and mitigate further impacts. Since Atlantic and coho salmon are not yet successful invaders in Chile, research attention is urgently needed to assess the environmental consequences of escapes of these species. The present approach can be applied to any aquaculture system given the availability of information on farmed species and receiving ecosystems.

KEYWORDS
aquaculture governance, biological invasion, Chilean Patagonia, exotic species, salmonid aquaculture

1 | INTRODUCTION

Aquaculture is of global relevance for food security and expected to provide most of the aquatic-origin protein for human consumption by 2050.[1] A large proportion of aquaculture relies on non-native species (NNS)[2–4] and this is likely to continue, thus presenting an increasing threat for ecosystems. Addressing the environmental impacts and understanding far-reaching consequences of NNS escapes is imperative, including the difficulties of recapture and control.[5,6] Large numbers of escapes may come from industrial farming, but also from small-scale aquaculture as the accumulation of many small events. Permanent escape of farmed NNS individuals may result in the establishment and spread of new species if individuals successfully reproduce in the wild. This has been shown globally for several ornamental[7] and farmed species such as salmonids,[8,9] tilapia and channel catfish.[10,11] Impacts could be especially relevant when aquaculture occurs in pristine and ecologically relevant ecosystems that often do not have enough surveillance nor mitigation mechanisms.

A significant portion of research and monitoring efforts to study aquaculture-origin escapes and their environmental consequences originate from salmon farming,[3,6,12,13] not because it has the most escapes, but because it takes place in more developed countries thus generating more mandatory reporting on escapes, more studies, and publications. Calls to incorporate risk assessments in policy formulation have been frequent in both native and non-native salmon environments.[6,13,14] Similarly, for non-salmonids species, efforts are increasing regarding extent and potential impacts of other escaped farmed species (e.g., tilapia,[11] sea bream and sea bass[15]). Yet, few studies have attempted to provide empirical risk assessments and practical recommendations to prevent and minimize the negative consequences of escaped farmed fish,[15,16] but mostly in salmonids.[11,17–19]

Globally, the most feared situation occurs when a non-native species expands its range and becomes an invader, resulting in negative effects on receiving ecosystems.[3,20] Aquaculture systems, especially floating net pens or rafts, are exposed to accidental loss or forced release of individuals. Escapes occur due to careless handling from human operators, structural failures of equipment during extreme environmental events (e.g., earthquakes, tides and waves, storms, flooding, tsunamis), third-party intervention (e.g., vandalism or theft), or the action of native predators, and even unknown causes.[12,13,19,21,22] A comprehensive assessment of the potential impacts of escaped farmed fish at multiple spatiotemporal scales is a difficult task, given the complex ecological, social and economic aspects that often include lack of information, resources and political will to address these impacts.

Here we use the case of intensive farming of NNS salmonids in Chile to explore the different components of risk associated with escapes supported by a review of relevant information over a large geographical scale. The review involves both the number of farmed and escaped individuals as well as other factors that may affect environmental risks for natural ecosystems and biodiversity. We use information about the aquaculture systems, production numbers, characteristics of the farmed species, as well as of the ecosystems that host aquaculture to estimate risks associated with escaped individuals. To achieve this objective, we use a simple framework adequate for participatory processes supported by the best scientific information and amenable to continuous improvement and field validation.

Chile is the world's second largest salmon and trout (thereafter referred as 'salmonid') aquaculture producer with about 1 million tons harvested in 2020, representing near US$ 4.5 billion in revenue.[23] This intensive aquaculture of NNS has generated employment and helped reduce poverty in some cities and coastal communities.[24,25] Also free-living salmonids have sustained recreational and artisanal fisheries,[12,26] even though commercial fishery of these species is illegal with few exceptions.[27] The introduction of salmonids in Chile began at the end of the 1800s to promote recreational fisheries of brown (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*), however, the negative ecological impacts of these introductions including escapes from aquaculture have only been documented recently.[12,21,28,29] One outstanding finding is that salmonid species seem to have differential success in establishing self-sustaining populations.[8] About 75% of the farmed salmonids in Chile is Atlantic salmon (*Salmo salar*), the only species not yet found in the wild. In contrast, rainbow trout (*O. mykiss*) represents only 8% of the aquaculture production, but it has extensive self-sustaining populations along the country,[30] with demonstrated negative impacts in freshwaters[29] but an attractive opportunity for recreational fisheries. Coho salmon (*O. kisutch*) represents 17% of the aquaculture production, but it has been reported as 'potentially established' only in very few places.[31] Regardless of their current establishment in the wild, any salmonid escapes could have negative impacts to receiving ecosystems.

Salmon escapes occur frequently in Chile,[21] with magnitudes relatively proportional to their production.[32] During the past 10 years, more than 3.8 million salmon have been reported as escaped.[33] Local fisheries partially mitigate these escapes, and they represent a promising although controversial tool for controlling free-living salmon.[12,26] However, concerns about the consequences of escapes over time for the receiving ecosystems have remained unattended.[28,34] Consequences of escapes include predation on and competition for prey with native fish, birds, and marine mammals, particularly with those species that are endangered or vulnerable[35] or that experience overexploitation,[36] and other unknown impacts on pelagic and benthic communities. In freshwater ecosystems, long-term consequences may take place after successful reproduction due to juveniles and adults in the case of trout[29] and due to juveniles of anadromous salmon. These species later migrate to marine environments for most of their adult feeding life and therefore potentially generating long-term consequences.[12]

Dissemination of diseases to wild fauna is also possible but its impacts on native species are not well documented.[37,38] Intensive salmon farming in Chilean Patagonia occurs in highly diverse marine ecoregions[39] within an intricate array of channels, fjords and sounds facing a narrow shelf, and fed by abundant river drainages.[40] Some of

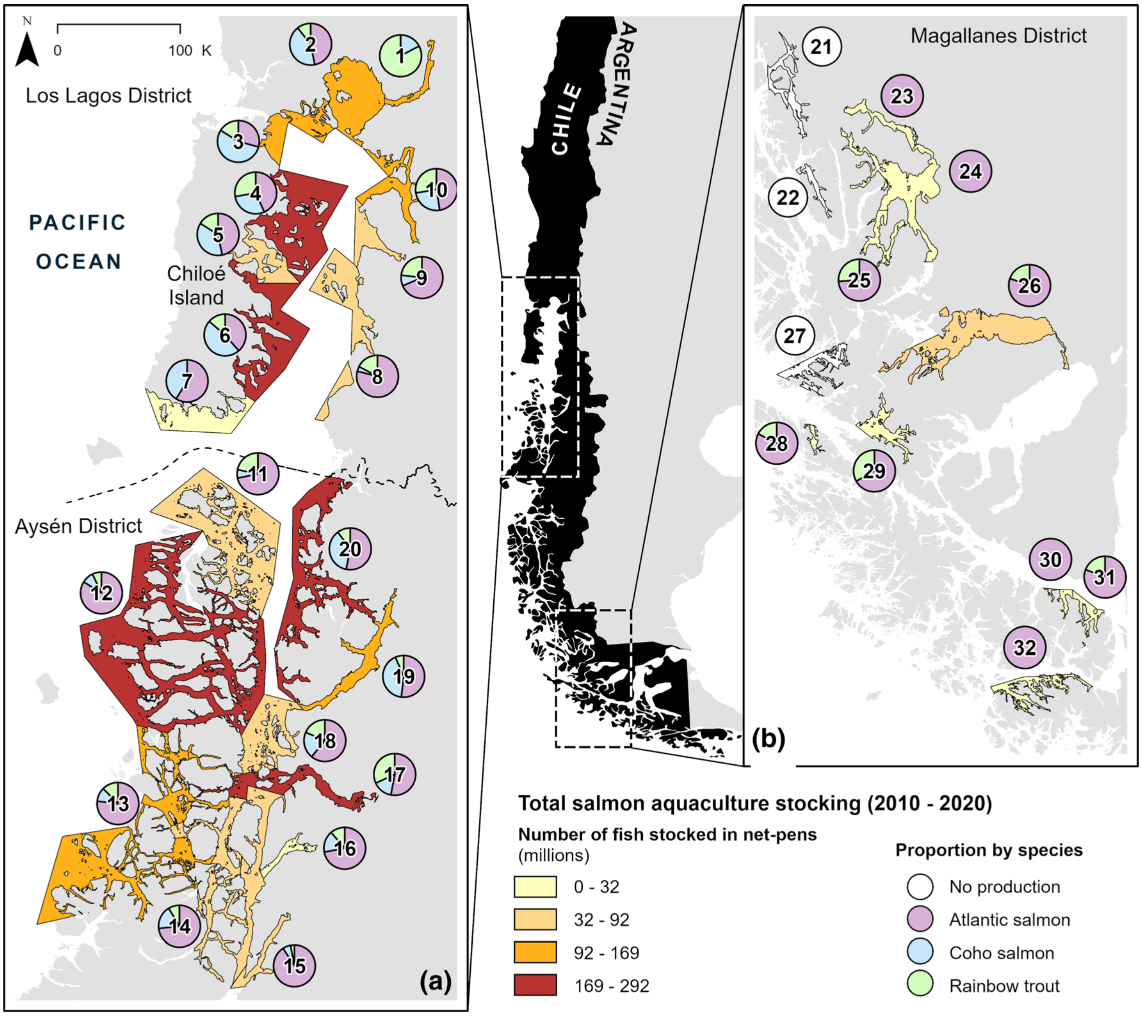

FIGURE 1 Accumulated number (millions) of stocked salmonid by species (2010–2020) in farms within 32 relevant water bodies (RWB) of southern Chile. Distributed by Districts. *Los Lagos District*: (1) Estuario Reloncaví. (2) Seno Reloncaví. (3) Achao. (4) Quemchi-Mechuque-Dalcahue. (5) Quinchao. (6) Queilen to Quellón. (7) South Quellón. (8) South Chaiten. (9) Reñihue. (10) Llancahue-Comau. *Aysén District*: (11) North Guaitecas. (12) South Guaitecas. (13) W I. Melchor-I.Luz. (14) E Walker-C Costa. (15) Cupquelan. (16) Quitralco. (17) F. Aysén. (18) Pto Aguirre. (19) Puyuhuapi. (20) I. Magdalena-Melimoyu. *Magallanes District*: (21) I. Owen. (22) Taraba. (23) North Natales. (24) South Natales. (25) Bahía Tranquila. (26) Seno Skyring. (27) Campo Nevado. (28) Cordova. (29) Xaultegua. (30) Petite. (31) I. Arrison. (32) I. Prowse

these waterbodies belong to ecoregions of global conservation priority[41] because they hold some of the world's most singular marine ecosystems, with high levels of endemism.[42–44] Considering that more than 360 million fish are stocked in Chilean every year (Figure 1),[23] it is critical to understand the potential consequences of salmon escapes on the sustainability of the receiving ecosystems at multiple spatial and temporal scales. There is also an opportunity to explore available information over a large geographical extent, involving 32 coastal marine areas that we identify as 'relevant water bodies' (RWB) (Figure 1).

While there have been few studies following the potential impacts of farmed salmon escapes,[12,21,27,28] there is no current field evidence or continuous monitoring that allows resource managers to clearly establish harm to species and ecosystems. The expansion of salmonid farming in remote areas of Chilean Patagonia has raised concerns in the scientific community and society at large regarding impacts from escapes. Here, we attempt to address such concerns by performing a semi-quantitative risk assessment to describe the comparative likelihood and potential environmental consequences of escaped salmonid species in southern Chile based on available information and acknowledging uncertainties. The assessment can be specially relevant to inform more targeted monitoring and field evaluation of impacts, currently very weak.

The analysis is performed in the RWB that contains salmonid farming in Chilean Patagonia (41.5–53°S; Figure 1) at the time of the information review (up to 2018) and we estimate risks associated with each salmon or trout species based on a matrix of weighted scores that includes an evaluation of *Hazard*, *Sensitivity*, and *Exposure* (Figure 2). Our approach also considers risk components that might facilitate the survival and eventual establishment of salmonid populations. We base our analysis on a large review of existing scientific information, the expert assessment of the authors, as well as the

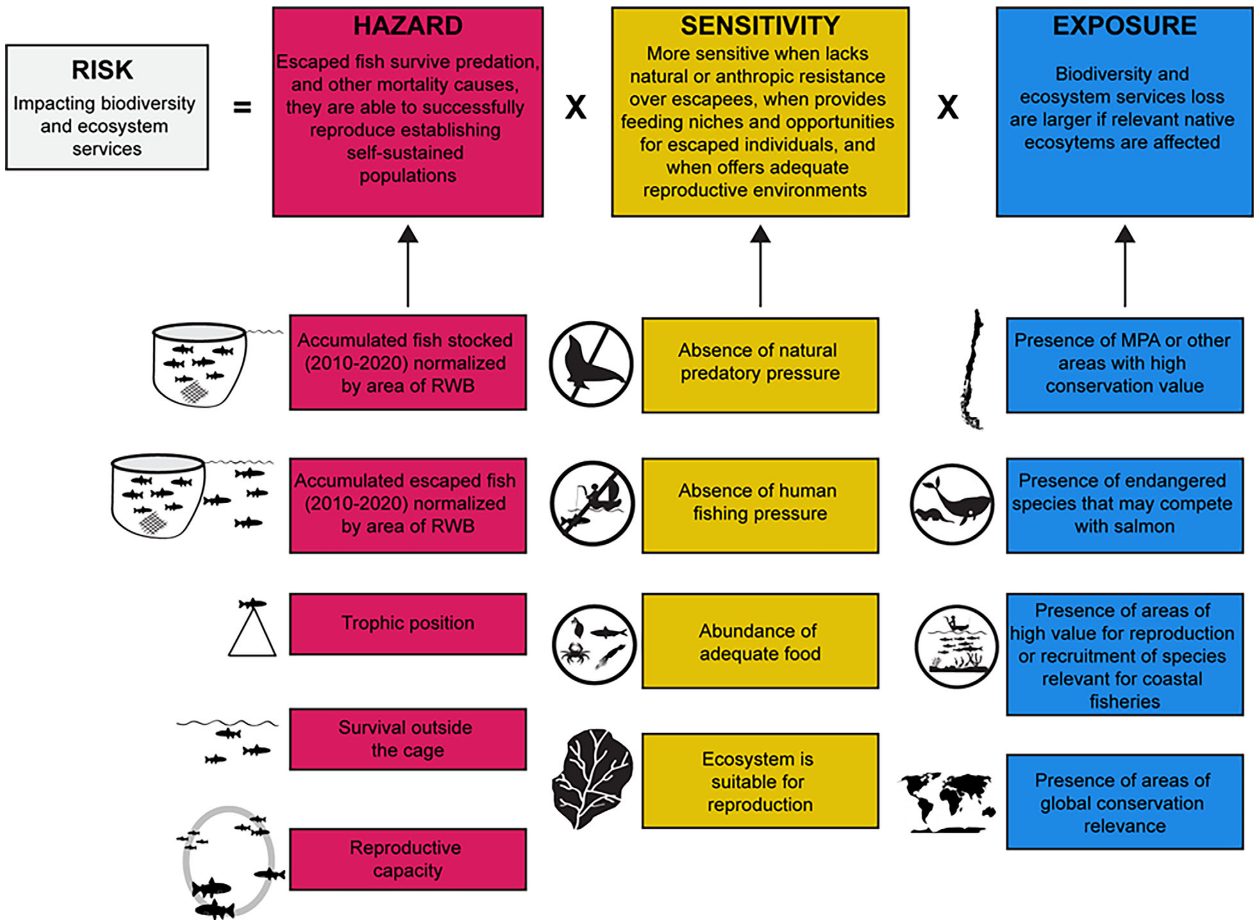

FIGURE 2 Approach to assess the risk of impacting biodiversity and ecosystem services from aquaculture escapes in a relevant water body (RWB). Risk = *Hazard* (red) × *Sensitivity* (yellow) × *Exposure* (blue). The main indicators used to build each of the components are shown as text boxes. MPA, marine protected areas

identification of uncertainties. This approach is simple and transferable across regions and other NNS used in aquaculture, providing an opportunity for science based participatory processes and decision-making to guide further research, preventive measures as well as to promote monitoring of specific areas according to risk levels and information gaps.

2 | METHODS

2.1 | Study region and risk assessment units

In Chile (40–50°S), salmonid fattening takes place in floating cages distributed in coastal systems ($n = 1400$ fish farming sites). Farming sites were grouped into 69 farming concession areas or neighbourhoods (ACS, in Spanish), assigned by the fisheries authorities mostly for sanitary management purposes.[12] Here, we regrouped ACS further into 32 relevant water bodies (RWBs). The definition of RWBs (Figure 1) is operational and can be improved with better information, especially regarding the ability of escaped salmonids to move between and beyond the defined RWBs. The criteria used here is described by Soto et al.,[45] and included (i) boundary conditions and physical and oceanographic features that could limit the passage or flow of water, particles, and species, and (ii) in more complex and/or open systems (e.g., channels) without clear oceanographic/physical boundaries, we used general oceanographic characteristics such as water renewal, pycnocline dimensions, temperature and oxygen conditions in the water column and bottom.

For each RWB (Figure 2), we estimated ecosystem impacts due to salmonid escapes such as predation and competition associated with each of the three species (impacts could last 3 or 4 years as the likely lifespan of an escaped individual), and impacts involving the establishment of new/additional salmonid populations resulting in the prolongation of impacts. For the assessment of risks, we also considered the watersheds that connect with each RWB and that could provide suitable reproductive habitats.

Due to the high complexity of interactions and ecosystem processes, including the extent of potential impacts and the lack of sufficient information, the risk approach used here includes proxies and indicators (Table 1) that oversimplify some processes and interactions. However, we used the resulting risk values only comparatively to highlight geographic areas and risk components that need urgent monitoring and management.

TABLE 1 Rationality of the adopted scoring system for each risk component (from 1 to 5) including assumptions and uncertainties

Risk component indicator				
Scores		Rationality and supporting evidence of adopted scoring classification among risk factors	Main uncertainties	Certainty level for the scores
Hazard				
Accumulated number of stocked fish (2010–2019)				
Atlantic salmon Coho salmon Rainbow trout	1–5 1–5 1–5	A proportion of stocked fish can escape by small unnoticed 'leaking' during farm handling.[13] Massive escapes due to extreme weather events were assumed proportional to the number of fish stocked in each RWB. Hazard scores assigned using quintiles from the overall distribution of stocked fish.	The assumption of equal proportion of small escapes for all RWB has not been evaluated in the field or using models. Hazard seems higher in some RWB, such as Seno de Reloncaví, regardless of the number of stocked fish	High
Accumulated number of escaped fish				
Atlantic salmon Coho salmon Rainbow trout	2–5 2–5 2–5	Most escapes were due to extreme weather events. RWB with greater accumulated records of escapes could be more likely to experience new events. Scores correspond to quintiles from the overall distribution of reported fish escapes. A score of 2 was assigned as a conservative value for RWB lacking escape records. A proportion of stocked fish can escape by small unnoticed 'leaking' during farm handling.[13]	There are no comparative field evaluations of escape hazard by RWB.	Medium
Estimated species survival after escaping				
Atlantic salmon Coho salmon Rainbow trout	3 4 4	There is an apparent depletion curve of recapture after massive escapes[12,26] that suggests lower survival of Atlantic salmon than rainbow trout and coho salmon. It's assumed that the dispersal of farmed salmon escapes was similar among species. A score of 5 should represent the highest survival rate based on Soto et al.[12]	There are no survival studies on escaped salmon in Southern Chile. It is unclear if gill nets used in available studies had similar catchability for all salmon species.	Low for Atlantic salmon, medium for coho salmon and high for rainbow trout
Estimated trophic position and impact of the farmed species				
Atlantic salmon Coho salmon Rainbow trout	4 3 5	Scores corresponded to quintiles of potential (maximum) daily consumption by species computed using bioenergetics models compiled for coho salmon and rainbow trout by Deslauriers et al.,[50] and for Atlantic salmon by Smith et al.[51] It was assumed that prey search and prey encounter probabilities for farmed salmon escapes were similar among species.	Realized consumption in the field can be quite different from estimated maximum consumption estimated under controlled (lab) conditions. Induced bias may differ between species and impacted ecosystems.	Medium for both Atlantic and coho salmon and high for rainbow trout
Ability of the species to reproduce in surrounding freshwater systems once free				
Atlantic salmon Coho salmon Rainbow trout	3 4 5	Scores accounted for differences in life history plasticity[8] and empirical evidence of presence/absence of juvenile fish in Chilean freshwaters including few reports for Coho salmon and practically none for Atlantic salmon, while rainbow trout has been able to colonize most south American watersheds.[29,31,52–56]	Lack of evidence of reproductive success at multiple basins for both coho and Atlantic salmon could be influenced by limited sampling efforts, especially in remote areas with difficult access.	Medium-High

TABLE 1 (Continued)

Risk component indicator				
Scores		**Rationality and supporting evidence of adopted scoring classification among risk factors**	**Main uncertainties**	**Certainty level for the scores**
Exposure				
Presence of marine protected areas (MPA) and of wetlands within or nearby RWB				
Similar for the three species	1–5	Marine protected areas were created to conserve native biodiversity hotspots and ecosystems for both pelagic and benthic species, maintaining the native conditions of the ecosystems conserving species and supporting local livelihoods.[94,95] Scores were assigned only based on distance from salmon farming facilities to RWB. It was assumed equal biodiversity for all RWBs. Some marine protected areas are also connected to estuarine and freshwater habitats.	There is no quantitative information on the amount and extent of biodiversity and ecosystem services that could be lost due to salmonid escapees nor about effective damage.	Low
Presence of native species under some conservation status				
Similar for the three species	1–5	Escaped salmonid would compete with piscivore native species, for sardines, anchovies, and fish alike. This might affect the food availability of endangered species including the Humboldt penguin, (*Spheniscus humboldti*), Chilean dolphin (*Cephalorhynchus eutropia*), the marine sea otter (*Lontra felina*) and the freshwater otter huillin (*Lontra provocax*).[12,96] Scores represented estimated presence of each endangered species in the area then an average score is generated for each RWB based on expert elicitation.[97] The three salmonids have been reported feeding on marine species in a couple of escapees-follow up studies.[12,28]	Relative abundance of endangered species in each RWB is unknown. The degree or competition for food between endangered species and any of the salmonid species has not been tested.	Low
Presence of reproductive areas of relevant fish species that are already overfished in the vicinity of RWB				
Similar for the three species	4–5	We used a score of 5 in 'special areas in the ocean that serve important purposes to support the healthy functioning of oceans and the many services they provide' (EBSA) category covering Los Lagos and Aysén fjords and channels. According to Castilla et al.[42] the southern marine region to the WWDC EBSA (Magallanes District) shared similar ecological characteristics, but since is not officially an EBSA, we assigned a lower score (4).	According to the CBD guidelines, the identification of EBSAs 'should use the best available scientific and technical information and integrate the traditional, scientific, technical, and technological knowledge of indigenous and local communities'. That might not be comprehensive for all the study area. Since more information is needed for the Magallanes District.	Low-medium
Sensitivity				
Capacity of artisanal fishermen to capture escaped salmon				
Similar for the three species	1–5	Artisanal fishery can be effective capturing escaped salmonid.[12,26] RWB with larger number of fishermen could capture more escaped fish. Comparative scores among RWB were generated according to geographical distribution of fishermen. Score = 1 assigned to the superior quintile of the distribution indicating the RWB with largest fishermen population. Score 5 = absence of fishers (more information in Supplementary material).	Fishermen effectiveness could depend on their boat and fishing gear characteristics, experience, availability to fish, and other factors. Numbers used here may underestimate population of fishermen since not all of them are registered and many local people informally fish for escaped salmon with gillnets from the shore.	Medium

(Continues)

TABLE 1 (Continued)

Risk component indicator				
Scores		Rationality and supporting evidence of adopted scoring classification among risk factors	Main uncertainties	Certainty level for the scores
Capacity of sea lion populations to capture escaped salmon				
Similar for the three species	1–5	RWB with larger number of resident sea lions are more likely to cause increase mortality of escapes by predation.[21] Comparative scores among RWB were generated according to distribution of sea lion numbers. Score = 1 was assigned to the superior quintile (the RWB with largest sea lion population size). Score 5 = absence of sea lions in the area.	Effectiveness of salmonid predation by different sea lion populations may vary according to sex and age classes of the individuals. Also, there is limited information on the foraging areas used by sea lions from the different colonies in the study area. The distribution and abundance of sea lions are not so comprehensive for the Magallanes district.	Medium
Ecosystem suitability for reproduction and early rearing				
Atlantic salmon Coho salmon Rainbow trout	1–5 1–5 1–5	For coho salmon and rainbow trout, we used available habitat intrinsic potential (HIP) models. Scores represented the availability and density of environments suitable for reproduction and early rearing (HIP index > 0.5, more information in Supplementary material).	Limited availability of fine-scale information about geomorphology and hydrology might affect HIP model outputs. Higher uncertainties in parameters used for the HIP model of Atlantic salmon. A detailed map of potential physical barriers to salmon upstream movement is not available.	Medium

Note: Detailed information on individual scores per each relevant water body are available in the Supplementary Tables.

2.2 | Risk definition and components

We defined risk (*R*) as the product of the probability (*P*) of an event occurring and its potential consequences (*C*); the latter is often described as the magnitude of the impact. In the literature,[12] there are various approaches for estimating risk, including: (i) estimates based on the measured impacts of similar activities in similar environments or contexts; (ii) estimates based on results validated numerically, semi-empirically or using empirical models; (iii) estimates based on accepted theory of cause–effect mechanisms; and (iv) expert(s) elicitation and opinion(s). Estimates of risk can be maximized if more than one of these approaches is applied.[46,47] Here we used a combination of these approaches.

We used a modification of the framework proposed by IPCC AR5[48] to address climate change risks described by Soto et al.[45,49] In this simple model (Figure 2), risk is a function of *hazard* (*H*), *exposure* (*E*), and *vulnerability* (V), where V is a function of *sensitivity* (*S*) and *adaptation capacity* (AC) such that $R = H \times E \times (S \times (1 - AC))$. In our case, however, we did not consider AC and assumed AC = 0, due to the lack of appropriate adaptation indicators. Future efforts to incorporate AC need to consider additional geopolitical scales, probably communes or municipalities. *H* represents the external pressure that is likely to cause an impact and is estimated from the number of fish farmed (stocked) and the reported escapes that occurred during the past 10 years. Additionally, this component included indicators representing the ability of the fish to survive outside the farming pens, and their trophic impact (Table 1). *S* represents aspects or characteristics of receiving ecosystems that make them more susceptible to experience negative outcomes associated with escapes. *E* represents what can be lost in terms of biodiversity and ecosystem services that would be deteriorated due to impacts of escaped salmonid, and the long-term impacts of escaped-origin offspring that successfully established self-sustained populations.

$$R = H \times S \times E \tag{1}$$

Outputs from the simple risk model shown in Equation (1) can then be applied to local sites, regions, or macro zones, and used to generate prevention recommendations and mitigation measures focusing on highest risk areas. This approach can be used to create scenarios where we can adjust *S* and *H* to determine priority actions and measures.

In our case, we created a semi-quantitative matrix that included a scoring system (1–5) for each of proposed indicators aiming to describe the components *H*, *S* and *E* (Figure 2). Score intervals were defined by setting the lower limit of the highest risk values and dividing the rest into four equal intervals. The highest score interval was assigned as an expert precautionary decision based on the authors' criteria (Table 1). This methodology can be useful when using the risk values for comparative purposes and prioritization of management measures.[49] In the case of qualitative estimations (e.g., survival away of pens) authors of the present document, which have an adequate background and knowledge of the subject in the field discussed and agreed on final 'experts scores'. However, we also used a 5-point score system to judge the certainty of the estimated indicators and resulting risk components and the final certainty score for the risk value was estimated as the mean of the score for each component. The scoring was based on the quantity and quality of the knowledge and information available to support an assessment.

2.3 | Assessing risks

2.3.1 | Hazard components

Number of fish stocked and reported escapes in 2010–2020

We used the cumulative number of juvenile salmonids stocked in cages per RWB for each species as an indication of productive cycle pressure; the more fish in an area the more likely it is to find escapes in the wild, even if these are resulting from permanent, small, nearly unnoticeable 'leaking' (e.g., during net cleaning and replacement). This number may be representative of the current salmonid farming potential escape *hazard* per ACS and per RWB. Values were obtained from SERNAPESCA through the Transparency Information System. Using the numerical distribution of accumulated stocked fish/km^2 per RWB between 2010 and 2020 for each species, we assigned a score value from 1 to 5 where all units (RWB) that have received fish numbers within the highest quintile were scored as 5. A similar approach was used to generate a score representing the accumulated number of escaped fish (Table 1 and Tables S1–S9, also see Soto et al.[49] for the scoring method). Both the number of stocked fish and number of escaped fish are periodically reported to and informed by the National Fishery Service of Chile (SERNAPESCA).

The information provided on escaped fish per salmonid farming area also included the main cause of the escape. We used local wind data (weather stations with online information) and numerical simulations (1 km spatial resolution) available on the Wind exploring Web platform (http://eolico.minenergia.cl/exploracion) to evaluate the importance of extreme weather conditions on the magnitude of escapes in our study region.

Survival of escaped salmonids

We used the only published information about survival of escaped salmonid in Chilean waters[12] to generate a comparative survival score for escapees of the three species. By comparing estimated artisanal fishing catches to available biomasses predicted by species from reported massive escape events, Soto et al.[12] estimated maximum instantaneous mortality rates between 0.8 and 1.2 (mean = 1.0) both for coho salmon and rainbow trout, and 1.2 for Atlantic salmon. We re-scaled these numbers to scores of 4 and 5, respectively (Table 1). The accumulated number of fish stocked in farms in each RWB between 2010 and 2019 and the reported number of escaped fish during the same period were selected as the only two quantitative indicators of *hazard* available for this purpose.

Trophic interactions and impacts

We ranked farmed salmonid species by maximum (potential) consumption rates as predicted by species-specific temperature-dependent functions and parameters compiled by Deslauriers et al.[50] for coho salmon and rainbow trout, and by Smith et al.[51] for Atlantic salmon. Using a theoretical mean weight of 500 g per escaped fish, consumption estimates were produced for each species and temperature records available between March of 2009 and March of 2015 were then averaged per RWB, and finally ranked using overall (across species) *hazard* quintiles (Table 1).

Reproductive capacity

We used an indicator of potential reproductive capacity to represent the ability of each species to establish new populations based on life-history plasticity and existing empirical evidence of self-sustained naturalized populations in the region. To do this, we assigned scores that accounted for differences in life-history plasticity based on Arismendi et al.[8] and empirical evidence of presence/absence of juvenile fish in freshwaters.[29–31,52–56] We assigned the maximum score (5) to rainbow trout (longer lifespan, long freshwater residency, iteroparity), moderate score (4) to coho salmon and the lowest score (3) to Atlantic salmon. See Table 1 for more information.

2.3.2 | Estimation of sensitivity components

We considered that a RWB with high fishing or predatory pressure (from sea lions) on escaped salmon would be less susceptible to suffer impacts from escapees than a water body that does not have such 'natural' and anthropogenic controls.

Salmon captured by artisanal fishing

Artisanal fisheries have been a practical way to recapture escaped salmon since fishers are efficient in doing so and some of the species such as Atlantic salmon seem to remain close to the aquaculture farm area for some time. Soto et al.[12] described the survival and mortality rate of escaped Atlantic salmon, rainbow trout and coho salmon, showing that Atlantic salmon tends to be captured more and disappear faster from the ecosystem. To estimate the fishing pressure potential on escaped salmon we used the database of registered artisanal fishers per coastal village by 2018,[57] then we clustered coastal village fisher numbers for each RWB (Table 1, Table S4) for the three salmon farming districts.

Sea lion predation on escaped salmon

We considered that a RWB with high fishing or predatory pressure (from sea lions) on escaped salmon is less susceptible to suffer impacts from escapees than a RWB that does not have such 'native species' control. To estimate the predatory pressure by sea lions on escaped salmon, we estimated the number of sea lions for each RWB according to the last census available in the area.[58] Different colonies reported by Oliva et al.[58] were assigned to the different RWB and the total number of sea lions for each colony was considered. Using the numerical distribution of sea lions per RWB we assigned a score from 1 to 5 as described above.

Abundance of adequate food

We do not have an estimate of available suitable food for each species for each RWB, therefore we assumed food is available and not limiting. We used the same score (4) for all species only to remind us of the high relevance of this indicator which, with better information could be modified in the future, representing specific conditions to support each farmed species.

Ecosystem potential for reproduction

Since most salmonids are anadromous, it was necessary to evaluate the potential of freshwater ecosystems to provide reproductive habitats for each species. We implemented the Habitat Intrinsic Potential (HIP) model[59] using all basins (>1.0 km^2) that drained directly into each RWB. This model evaluates the suitability of physical conditions to support spawning and early rearing habitats based on species-specific habitat requirements.

We generated synthetic drainage networks for each basin based on a Digital Elevation Model of 12.5 m resolution using ALOS PALSAR – Radiometric Terrain Correction[60] and a model of mean annual precipitation (WorldClim 2.1) of 1 km resolution. Drainage lines were segmented into 100 m and 1000 m river sections and characterized using instream geomorphic characteristics including drainage area, precipitation, modelled channel width and depth, discharge, gradient, water velocity, valley confinement and habitat connectivity. Channel gradient and valley confinement were estimated from elevational changes in the DEM.[61] Spatially continuous mean annual discharge was modelled using multiple non-linear regressions between drainage area and mean catchment precipitation from 82 gauging stations in the region (CAMELS-CL, CR2).[62] Discharge models were fitted separately for three different hydrological districts (Los Lagos, Aysén and Magallanes, Figure 1), which showed satisfactory performance ($R^2 = 0.97 \pm 0.02$). Channel geometry (i.e., channel width and depth) was obtained using a similar approach, but by invoking published regional regressions for South America.[63] Water velocity was calculated based on reach gradient and modelled channel depth and width following Manning's equation.[64] We identified barriers to fish migration based on the gradient of stream reaches and species-specific movement traits,[59,65,66] complemented with documented human-made barriers (e.g., hydropower dams; $n = 3$)[67] and natural barriers (e.g., waterfalls; $n = 321$, queried from Open Street Maps in July 2021).

For the reclassification of environmental conditions, we first selected variables and generated relationships for each species separately. We aggregated existing published HIP models[66,68] for coho salmon and rainbow trout. Given that no explicit HIP studies were available for Atlantic salmon, we formulated a HIP model based on published evidence obtained from similar modelling approaches based on PHASBIM (Physical Habitat Simulation Model), HABSCORE and related techniques.[69–72] We selected all stream sections with HIP scores above 0.5 and estimated their abundance and density near each RWB. The sum of linear kilometres with potential habitats and their density in relation to the total accessible linear kilometres was reclassified using an equal-interval classification system. This resulted in an indicator representing abundance of reproductive environments and an indicator of their density, ranging from 1, representing RWBs with the lowest potential for reproduction, to 5, representing RWBs with the highest availability and density (higher potential for reproduction).

2.3.3 | Estimation of *exposure* components

We estimated the ecosystem *exposure* to escaped salmon as a combination of highly valuable ecosystems, habitats, biodiversity, and fishery resources that could be lost due to the temporal or permanent impact of escaped salmon. We considered these as the components of *exposure*, however they were just proxies of ecosystem services and biodiversity that could be lost; better and more comprehensive indicators can be built with better information and valuation of ecosystem services in the future.

To build the *exposure* indicator we produced scores for the following components (Table S9): (i) ecosystems and habitats that could hold/support relevant biodiversity such as protected areas or coastal wetlands; (ii) presence of endangered species that could compete for food with escaped salmon; (iii) presence of reproductive areas of fishery species that are relevant for coastal communities and in poor conservation status; and (iv) presence of areas of global conservation relevance.

To estimate component (i) we estimated the overlap between RWB and marine protected areas (MPA, marine reserves, marine parks, multiple use marine and coastal marine protected areas http://areasprotegidas.mma.gob.cl/, natural sanctuaries and national reserves) and coastal wetlands potentially exposed to salmon disturbance and foraging. For MPA we established the scores using the official protected areas database of the Ministry of the Environment, where we ranked the relative distance of the MPAs, where 5 was the presence of an MPA in the RWBs; 3 where the RWB was contiguous to another RWB with presence of a MPA, and 1 to RWB not contiguous to or with the presence of an MPA. For wetlands, the score was estimated by ranking the numerical distribution of the presence of wetlands (rivers, streams, marshes, and coastal wetlands) in contact with the marine environment and the RWB to which we assigned a score value from 1 to 5, using the information from the national inventory of wetlands (https://humedaleschile.mma.gob.cl/). To estimate a score for (ii), endangered species, we used the geographic distribution of native species classified as threatened (Critically Endangered (CR), Endangered (EN) and Vulnerable (VU)) in IUCN's Red List (https://www.iucnredlist.org/) or the national species classification status of the Ministry of the Environment (http://especies.mma.gob.cl/) that compete directly with escaped salmon for food. The selection of the threatened species included the piscivorous species, the Humboldt penguin, *Spheniscus humboldti* (VU), the Chilean dolphin, *Cephalorhynchus eutropia* (VU), and two sea otters, the marine otter, *Lontra felina* (EN) and the southern river otter, *Lontra provocax* (EN). The score was 5 if any of the water bodies overlapped with the distribution of the threatened species, using the published records and expert elicitation information.[73] To estimate (iii), the *exposure* of exploited commercial fish species, we established scores considering the recruitment and nursery grounds for three fish species with poor conservation status according to the annual official report[36]; the over-exploited Southern hake, *Merluccius australis*, and Southern blue whiting, *Micromesistius australis*, and the collapsed Patagonian grenadier, *Macruronus magellanicus*, using the maximum score of 5 for the RWB that overlapped the recruitment and nursery grounds.

Lastly, to estimate (iv), ecosystems of global significance we used the EBSA classification. The EBSAs are special areas in the ocean that serve important purposes mainly to support the healthy functioning of oceans and the many services they provide (https://www.cbd.int/

ebsa/about) considering 7 criteria: 1. Uniqueness or Rarity; 2. Special importance for life history stages of species; 3. Importance for threatened, endangered or declining species and/or habitats; 4. Vulnerability, Fragility, Sensitivity, or Slow recovery; 5. Biological Productivity; 6. Biological Diversity; and 7. Naturalness. In 2015, at CBD COP12, the West Wind Drift Convergence (WWDC) EBSA was declared. The area, covering pelagic through deep-ocean zones between, 41.5°S and 47°S off the coast of Chile (including fjords and channels and the offshore area up to 200 km from the coastline), comprises an intricate array of inner seas, archipelagos, channels, and fjords stretching some 600 linear km and enclosing roughly 10,700 km of convoluted and protected shoreline (https://chm.cbd.int/database/record?documentID=204089). This EBSA corresponds to the Aysén and Los Lagos Districts of Chile.

Accordingly, we gave a score of 5 to all RWB within the West Wind Drift Convergence (WWDC) area. The water bodies not within the WWDC EBSA were ranked with a 4, given the similarity to the WWDC EBSA and the high ecological and biological significance based on expert judgement (Table 1).

The full data and description of indicators can be found in Tables S2–S8 and an example describing the risk estimation approach is shown in Table 2.

3 | RESULTS

Atlantic salmon dominated production, with more than 50% of the fish stocked in almost every relevant water body (RWB). The magnitude of fish stocked per RWB ranged from 200,000 in the Reloncaví Fjord to more than 200 million in Guaitecas Sur (Figure 1; Tables S1–-S4). Coho salmon was only farmed in the northern portion of Patagonia, whereas rainbow trout, the least farmed species, was intensively produced in the Reloncaví (Los Lagos district) and Aysén district fjords (Figure 1).

During the studied period (2010–2020), 3,818,096 fish escaped from salmonid farm facilities and most large escapes are indicated as caused by extreme events. Unfortunately, the available information does not allow yet to assign an indicator for extreme events to all RWB. In fact, two of the largest escapes in the past 10 years have been caused by extreme winds, but similar winds have caused small or no escapes in other RWB (Figure 3).

Hazard scores among RWBs were mostly higher for rainbow trout than for the other salmon (Table 3). Since scores representing the cumulative number of escaped fish per area were assigned independently for each species, *Hazard* differences among them were only affected by the indicators of survival, trophic impacts, and reproductive capacity

TABLE 2 Example to describe estimation of risk

Indicators to estimate hazard		Indicators to estimate sensitivity		Indicators to estimate exposure	
	Scores		Scores		Scores
Indicator 1; N° stocked fish/km^2	2	Indicator 8; absence of fishing and predation by sea lion (average of indicators 6 and 7, see Table S5a)	4.5	Indicator 11; presence of MPA within or nearby to the RWB	3
Indicator 2; cumulative N° of escaped fish/km^2	4	Indicator 9; (availability of suitable food for escaped fish)	4	Indicator 12; presence of wetlands in the RWB	3
Indicator 3 = natural survival away from cages	3	Indicator 10; stream reproductive potential (see Table S5b)	3.5	Indicator 13; presence, navigation route of blue whale	nr
Indicator 4; trophic impact	4			Indicator 14; presence of Humboldt pinguin	nr
Indicator 5; reproductive capacity	3			indicator 15; presence of Chilean Dolfin	5
				Indicator 16; presence of *Lontra felina*	nr
				Indicator 17; presence of *Lontra provocax*	nr
				Indicator 18; composite of threaten piscivorus species	5
				Indicator 19; macroregional/global biodiversity relevance	5
				Indicator 20; presence of reproduction/recruitment areas of fish species relevant coastal fisheries and that reportedly overfished	5
Hazard (Av: Ind1…Ind5)	3.2	*Sensitivity* (Av Ind 8, 9 and 10)	4	*Exposure* (Av Ind 11…Ind 20)	4
				Risk = ($H \times S \times E$)/125 (3.2 × 4 × 4)/125	0.44

Note: Potential risk associated to Atlantic salmon escapes in the RWB 14_Estero Walker-Canal Costa (Figure 1). Scores range between 1 (lowest) to 5 (highest), nr = not reported or known.

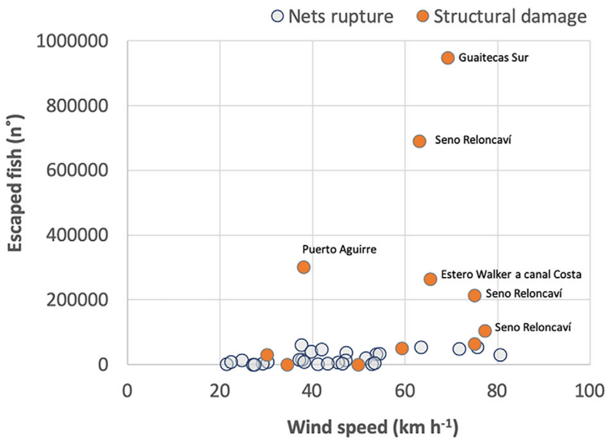

FIGURE 3 Reported escaped salmonids during extreme weather (wind) in the period 2010–2020

(Figure 2; Tables 1 and 3), all being higher for trout. *Hazard* differences among RWBs for the same species resulted from the number of stocked fish and the magnitude of reported escapes (Tables S2–S4). In general *Sensitivity* scores increased southward (Table 3), mainly because of declining abundance of sea lions as natural predators and fishers (Figure 2), regardless of the magnitude of the escapes. Fishers and sea lions played an important role in the potential control of escapes in both Los Lagos and north-eastern Aysén districts (Tables S5a and S5b). In contrast, there were very low abundances of both fishers and sea lions in the Magallanes district, leading to higher *Sensitivity*. This southward increasing trend in *Sensitivity* can be seen well for rainbow trout (Table 2) while it is masked by other factors in the case of Atlantic and coho salmon including the presence of basins more suitable for reproduction with the largest scores in Aysén (Table 3; Tables S5b, S6 and S7). Figures 4 and 5 describe habitat reproductive sensitivity for Atlantic and Coho salmon in this District.

Exposure scores were comparatively higher in the Los Lagos and Aysén districts than in Magallanes. This is because of the higher relative abundance of sensitive piscivorous native species (i.e., threatened Humboldt penguin, Chilean dolphin, and sea otters). Some areas in these districts were identified as essential nursery habitats for over-exploited fish such as the southern hake, *Merluccius australis* (Table 1; Table S8).

Final risks and risk components for each species and RWB are shown in Table 3. Certainty of risk estimations is also described in Table 1, and Table 3 includes certainty scores and colour scale showing the lowest levels in the case of Atlantic salmon and the highest for rainbow trout, mostly due to insufficient supporting field information.

The combination of *hazard*, *sensitivity* and *exposure* scores (Figure 2) per farmed salmonid species and RWB resulted in the highest risk for rainbow trout escapes compared to the other species (Table 3). The risk associated with the escape of any salmonid species by weighted average was higher in RWBs in Aysén district. Risks associated with Atlantic salmon escapes were relatively high in RWBs located in the southern and east areas of the Aysén district (RWB 14, Estero Walker -Canal Costa and RWB 20, Isla Magdalena-Melimoyu, Figure 1; Table 3). Coho salmon showed its highest risks mostly in the Aysén district (Table 3) and there were no risk values for Magallanes district since at the time of this study there was no reported farming occurring there (Figure 1).

As described above, risks for the three salmon species were influenced by the environmental potential of freshwater ecosystems to support the reproduction of each species (Figure 2; Tables S5–S7). Higher *Sensitivity* for Atlantic salmon in the eastern and southern portions of the Aysén district (Figure 4; Table S6) was influenced by higher availability of potential habitats for the spawning and early rearing in basins of the Palena, Cisnes, Aysén and Exploradores rivers. The distribution of potential habitats for reproduction and early rearing of coho salmon followed a similar pattern, reaching its highest scores in the Aysén district with the same relevant river basins as for Atlantic salmon. However, the preference of coho salmon for smaller streams[59] resulted in higher scores of potential reproductive habitats than for Atlantic salmon and rainbow trout (by one order of magnitude) and more availability of habitats in small basins such as those located at western islands in the Aysén district (Figure 5). As a result, we found higher risks of environmental impacts due to escapees for Atlantic and coho salmon mostly in the central and south Aysén district (Table 3).

At the time of this study, there was very low or no farming of salmonids in many RWB in the southernmost District of Magallanes (Figure 1), but this situation may change as increasing salmon production is expected in this region. Therefore, we use the approach to model comparative risks associated to a hypothetical large escape of any of the species considering similar stocking of the three species in all RWB. Thus, risk patterns and differences (Table 4) are only associated with 'survival and invasive' characteristics of each species and habitats *sensitivity* and *exposure* (Tables 1 and 3).

4 | DISCUSSION

This study does not provide direct evidence of impacts of escapes of any of the species however, in the case of rainbow trout the harm generating risks has been well supported by numerous studies[29,32,34] although largely for freshwater ecosystems. For the other two species, harm has been inferred by studies describing stomach content of wild captured individuals which showed consumption of mainly crustaceans and fish[12,26,29] but the evidence of impacts in the field is limited. A follow up of a massive salmonid escape (involving the three species) from marine net-pens that took place in 1995[12] found a negative correlation between abundance and diversity of marine fish species and escaped salmonids abundance dominated, the latter dominated by rainbow trout and coho and lower representation of Atlantic salmon. Yet this is weak evidence of impact.

Since trout were successfully introduced in the country early in the 19 century, they have generated many studies which we are using to infer impacts while information about Atlantic and coho salmon is more limited. However, considering the trophic role of these species as efficient predators in their native habitats, and their use of both

TABLE 3 Summary of scores for *hazard* (*H*), *sensitivity* (*S*) and *exposure* (*E*) indicators and estimated risks for each species (Atlantic salmon, rainbow trout and coho salmon) per relevant water body (names as in Figure 1)

Relevant water body	Hazard Atlantic salmon	Sensitivity Atlantic salmon	Hazard rainbow trout	Sensitivity rainbow trout	Hazard coho salmon	Sensitivity coho salmon	Exposure	Atlantic salmon RISK	Rainbow trout RISK	Coho salmon RISK	Average weighted RISK
Certainty of the estimation	3.4	3.3	4.6	4.7	3.6	4	3	3.2	4.1	3.5	3.5
Los Lagos											
Es. Reloncavi	2.6	3.3	5	3.7	3.8	3.2	2.7	0.18	0.39	0.26	0.37
S. Reloncavi	3.6	3.0	3.8	3.5	3.4	3.0	4.0	0.35	0.43	0.33	0.35
A. Chacao	2.8	2.7	4.2	3.2	4.4	2.8	4.4	0.26	0.47	0.44	0.39
Quemchi-Mech-Dalcahue	3.4	2.7	4.4	3.2	3.4	2.8	4.0	0.29	0.45	0.31	0.34
Quinchao	3.2	3.2	4.2	3.7	3.6	3.3	4.3	0.34	0.52	0.41	0.40
Queilen a Quellon	3.2	2.8	4.2	3.2	3.8	3.0	4.0	0.29	0.43	0.36	0.34
Quellon Sur	2.6	3.0		3.3	3.2	3.0	3.0	0.19		0.23	0.20
Chaiten al sur	3.4	3.3	3.8	3.8	3	3.3	3.5	0.32	0.41	0.28	0.33
Reñihue	3.2	3.0	4.2	3.5	3.2	2.8	4.0	0.31	0.47	0.29	0.34
Llancahue Comau	3.4	3.2	4.4	3.5	3.6	3.0	4.6	0.40	0.57	0.40	0.44
Aysen											
Guaitecas Norte	2.6	2.7	4.4	3.2	3	2.8	3.3	0.24	0.48	0.30	0.29
Guaitecas Sur	3.4	3.5	3.6	4.2	3	3.8	3.8	0.37	0.47	0.33	0.38
W. Islas Melchor –Is Luz	2.8	3.7	3.6	4.3	3	3.7	4.2	0.38	0.54	0.42	0.40
E. Walker a C. Costa	3.2	4.0	3.6	4.5	3.2	4.2	4.2	0.47	0.58	0.47	0.48
Cupquelan	3.6	4.3	3.6	4.8	3.2	4.3	3.3	0.36	0.41	0.32	0.36
Quitralco	3.2	3.8	3.8	4.3	3.4	3.8	4.0	0.39	0.55	0.44	0.42
Fiordo Aysen	3.4	3.8	4.4	4.5	3.6	4.0	3.8	0.36	0.54	0.36	0.42
Pto Aguirre	3.4	3.5	4	4.0	3.4	3.3	3.8	0.36	0.51	0.36	0.39
Puyuhuapi	3.6	3.5	4	4.2	4	3.5	3.8	0.40	0.48	0.44	0.42
I. Magdalena-Melim	3.2	3.7	4	4.0	3.6	3.7	5.0	0.51	0.69	0.53	0.54
Magallanes											
Isla Owen		4.0		4.3		3.7	3.0				
Taraba		3.7		4.2		3.5	3.7				
Natales Norte	2.6	3.5		3.8		3.5	2.0	0.16			0.16
Natales Sur	2.6	3.0		3.3		3.0	3.5	0.25			0.25
Bahía tranquila	3.2	3.8	4.4	4.2		3.7	3.8	0.34	0.53		0.39
Seno Skyring	2.6	3.5	4	3.8		3.5	4.0	0.28	0.51		0.32
Campo Nevado		3.5		4.0		3.7	3.8				

(Continues)

TABLE 3 (Continued)

Relevant water body	Hazard Atlantic salmon	Sensitivity Atlantic salmon	Hazard rainbow trout	Sensitivity rainbow trout	Hazard coho salmon	Sensitivity coho salmon	Exposure	Atlantic salmon RISK	Rainbow trout RISK	Coho salmon RISK	Average weighted RISK
Córdova	3.4	3.3	4.2	4.0		4.0	3.8	0.31	0.46		0.33
Xaultegua	2.8	3.7	4	4.2		3.7	3.8	0.28	0.46		0.34
Petite	3.4	3.0		3.7		3.5	3.8	0.34			0.34
Isla Arrison	3.2	3.3	4	3.8		3.5	3.8	0.32	0.46		0.35
Isla Prowse	3	3.3		3.8		3.5	3.3	0.26			0.26

Note: Values and colours of risk components represent the average of several indicators fluctuating between 1 and 5 (scores) for *H*, *S* and *E*, and risks which can vary between 0 and 1 (Tables 1 and 2 and Supplementary Material). The final column represents the combined risks due to escapes for the three species, estimated as the weighted average (based on the proportion of stocked fish for each species, Table S9). Confidence level or certainty of the scoring and assessment of each risk component and final value is provided as per the authors estimate using a scale from 1 to 5 (and a colour scale), being 5 the highest certainty.

freshwater and marine ecosystems, grant enough concerns.[18] Also, evidence on the expansion and impacts of other NNS salmonids such as rainbow trout[29] and Chinook salmon[74,75] support such concerns. The fact that there is no evidence of successful establishment and impacts of Atlantic salmon in Chile and is very limited for coho salmon may also be masked by the lack of monitoring, especially in remote areas.[76] Therefore, this study achieves an important goal by identifying the highest risk RWB/areas and risk components since this could guide field validation and focus research attention to those components estimated with lower certainty (Table 3).

4.1 | Differential capacity to mitigate escapes as well as differences among escaped species influence risks

Using the presented approach, we can identify areas at high and low risk to be impacted by salmonid escapes across 1500 km of coastal systems in Chile. Risks of salmonid escapes for natural ecosystems will be always present if this aquaculture system persists in the future. Salmonid culture in marine farms will undoubtedly result in both small underreported and large-scale escape events. During the winter of 2018, a storm led to an escape of 680,000 Atlantic salmon of an average mass of 4.0 kg per individual in the Reloncaví fjord.[34] Fishers were able to recapture only about a third of the escapees, with some incidental predation by sea lions.[26] However, many unaccounted salmon could have died from starvation or remained in the area and beyond, affecting natural ecosystems.[12] Environmental risks associated with escapes of any salmonid species are high around Chiloé Island (Los Lagos district) and in the Aysén district (Figure 2, Table 3) due to the combination of risk factors associated with production, historical escapes, expected salmonid survival, their trophic role and the presence of natural predators, and fishers. Clearly, the capacity to mitigate salmonid escapes and therefore risks is highly dependent on the density and proximity of fishers and other predators to salmonid farms.

Several elements stand as relevant regarding differential risk levels in different RWBs. First, the capacity of sea lions to mitigate salmonid escapes although still unclear[21] cannot be underestimated. Second, the potential to use local artisanal fisheries as a mitigation measure[12] has been discussed by decision-makers, pending further studies and monitoring, but remains as an important control. Third, the fate and impact of different species once escaped can vary. Studies on escaped salmonid in Chile suggest that Atlantic salmon have lower survival and ability to feed after escaping compared to coho salmon or rainbow trout.[12,26,28] Although rainbow trout is the least farmed species, its high capacity to survive in the wild and trophic impact[8,29] results in high risks in RWB where this species is farmed (Tables 3 and 4). Therefore, if the main farmed species would be trout (instead of Atlantic salmon) the average weighted risks would be much higher than the ones estimated here. Risk could also increase if we would also include the transmission of diseases and parasites, but we do not have enough information yet to involve this factor. Fourth, more and larger salmonid farms could increase risks, especially if they

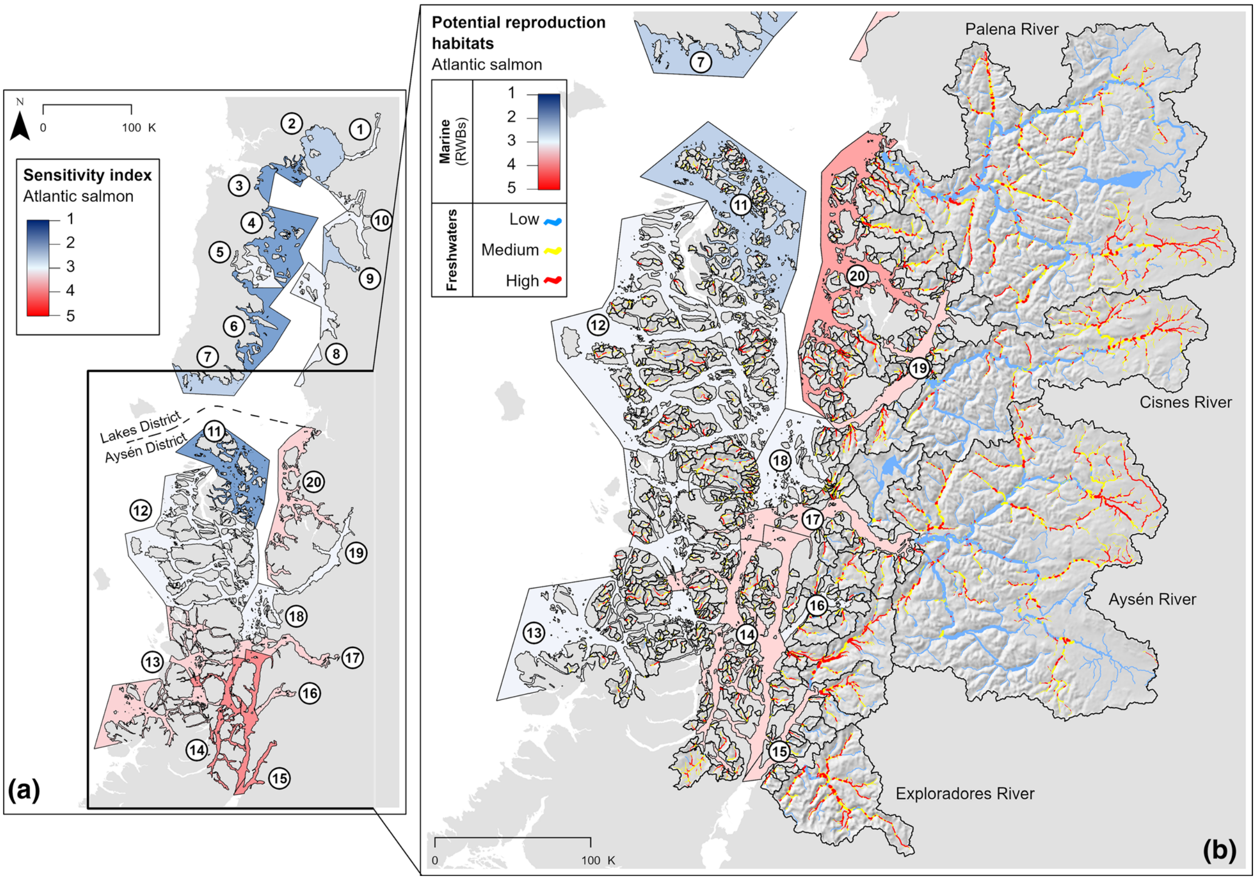

FIGURE 4 (a) *Sensitivity* index per relevant water body (RWB; $n = 20$) for Atlantic salmon. From low (blue) to highly (red) sensitive areas. (b) Example of results for the *sensitivity* to reproduction index in the Aysén district as one of the index components. The *sensitivity* to reproduction index represents the habitat intrinsic potential (HIP) for spawning and early rearing of Atlantic salmon within basins draining into each RWB. HIP values were classified as low (HIP index < 0.5), medium (0.5 < HIP index <0.75) or high (HIP index >0.75)

are in RWB where fishers and sea lions are not abundant such is the case of several RWB in Aysén and even more far south in Magallanes district (Figure 1). Also, if farms are exposed to more extreme weather events the probability of escapes is larger although we could not assess this within the *Sensitivity* component, and this should be included in the future especially considering that extreme events may increase with climate change.

4.2 | Risks and long term impacts depend on the escapees ability to reproduce and availability of habitats to support successful reproduction and early life stages

From the three farmed species, rainbow trout is the only species showing widespread naturalization and very high invasion capacity,[29,30,77] which is a relevant consideration despite its low representation in the salmon farming production (Figure 1). Also, risks associated with escapes of this species could be higher than anticipated because farmed trout have been selected for faster growth and resiliency.[78] The reproductive season for all salmon species in the wild is currently protected from recreational fisheries in Chile,[79] and rainbow trout aquaculture for stocking in support of recreational fisheries is a common practice in the Argentinian side of Patagonia.[80] Also, there is a potential for rainbow trout to transfer diseases and parasites to native species and to the already established trout populations. Hence, risks resulting from rainbow trout escapes are likely underestimated, while they are thought to offer livelihood options through recreational fisheries and associated tourism activities.

Habitats that show high intrinsic potential for reproduction and early rearing will result in higher *sensitivity* because they could effectively host juvenile salmonids, and this will lead to higher risks of establishment. Even though Atlantic salmon has been the most farmed species during the past 20 years[25] there are no reports of self-sustaining populations; some authors have argued that this species could be less adapted to colonize environments in the Southern Hemisphere. Comparison has been made with the invasion success of Chinook salmon in southern Chile and Argentina which, interestingly has not been generated by massive escapes, but rather by several sparse events and thus the successful colonization has been probably due to the ability of the species to colonize new habitats.[8,74,75] Nevertheless, there is no guarantee that continuing escapees of Atlantic salmon,

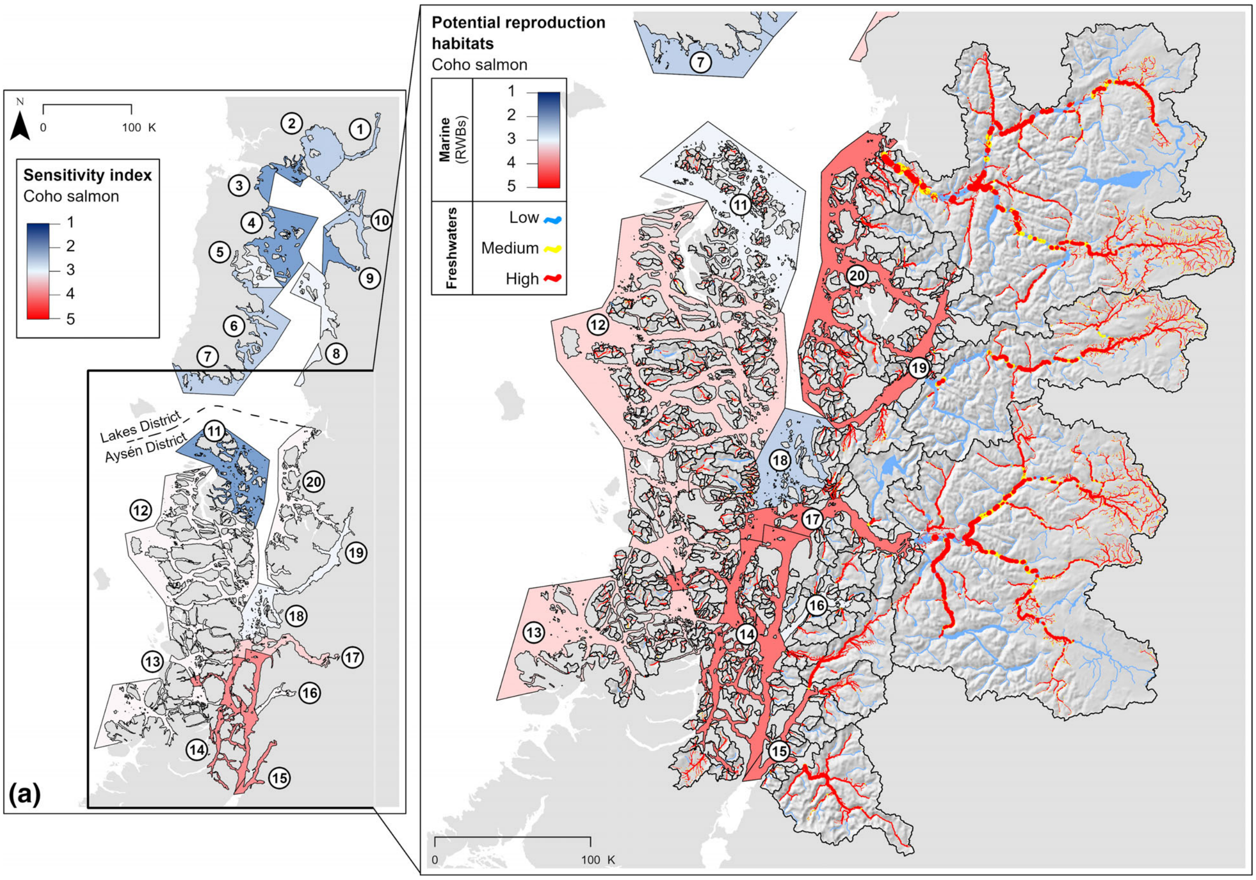

FIGURE 5 (a) *Sensitivity* index per relevant water body (RWB; $n = 20$) for coho salmon. From low (blue) to highly (red) sensitive areas. (b) Example of results for the *sensitivity* to reproduction index in the Aysén district as one of the index components. The *sensitivity* to reproduction index represents the habitat intrinsic potential (HIP) for spawning and early rearing of Coho salmon within basins draining into each RWB. HIP values were classified as low (HIP index < 0.5), medium (0.5 < HIP index < 0.75) or high (HIP index >0.75)

including new strains, cannot eventually result in successful establishment of wild populations.[18,81] Indeed, many relevant water bodies and hydrographic basins with high environmental potential for reproduction and early rearing of this species exist in the Aysén district (Figure 4) and also for coho salmon (Figure 5). However, some of these suitable freshwater habitats are in remote and less accessible areas with no direct assessments of reproduction success. The recent development of environmental DNA techniques to detect fish presence in streams[82] offer an interesting tool for field monitoring of the reproductive success of Atlantic salmon in these remote environments.

The risk assessment framework presented here can be used to evaluate potential risks of salmonid escapes in areas that are not currently occupied by farms or with low farm production but that could potentially grow in the future. This is shown in Table 4, where we explore the risks of a hypothetical large escape of any species in any RWB. For example, the southernmost Magallanes district is considered extremely pristine and with relevant cultural heritage.[83] Risks associated with Atlantic salmon in this district are still relatively small compared to the northern districts of Los Lagos and Aysén. Lower risk is strongly influenced by lower historical salmon farm production, but this could change if the production increases, especially in relevant water bodies with high *sensitivity* scores associated with the availability of suitable spawning and rearing habitats. Also, remoteness and difficult access to some of the farming areas are issues to control and monitor massive escapes. Thus, a large escape of Atlantic salmon would present higher risks in RWBs 25 Bahia Tranquila, 26 Seno Skyring, and 29 Xaultegua. Yet, the largest risk would be associated with coho salmon escapes in most RWB in that district (Table 4). This species has not been farmed in Magallanes, but our risk map offers a relevant warning against it. Such warning is also supported by recent findings of juvenile coho salmon in streams of this district, whose origin is attributed to escapes from the northern Aysén district.[31,53,76] This finding also challenges the boundaries of our study units, as escaped salmonids can move farther away from their respective RWBs. Interestingly, there is still no documented evidence of natural reproduction of coho salmon in areas with high farming production such as the Los Lagos and Aysén districts where a higher risk is due to the availability of spawning and early rearing habitats that increases the *sensitivity* scores (Figure 4). Regardless, the differential reproductive success of escaped farmed salmonid species is complex and likely driven by the interactions of species plasticity and environmental

TABLE 4 Comparative risks associated to a theoretical large escape considering similar numbers of stocked fish for all species in all RWB (from north to south), and hazard components intrinsic to each species (survival indicator, tropic index and reproductive capacity indicator). Hazard scores were then given the same value for all the RWB, and were 3.8; 5 and 4.3 respectively[a] for Atlantic salmon, rainbow trout and coho salmon

Relevant water body	Atlantic salmon	Rainbow trout	Coho salmon		Atlantic salmon	Rainbow trout	Coho salmon		Atlantic salmon	Rainbow trout	Coho salmon
Los Lagos				*Aysen*				*Magallanes*			
Es. Reloncavi	0.27	0.39	0.46	Guaitecas Norte	0.26	0.41	0.56	Isla Owen	0.36	0.52	0.52
S. Reloncavi	0.36	0.56	0.69	Guaitecas Sur	0.40	0.63	0.65	Taraba	0.41	0.61	0.63
A. Chacao	0.36	0.56	0.76	W. Islas Melchor –Is Luz	0.47	0.73	0.72	Natales Norte	0.21	0.31	0.34
Quemchi-Mech-Dalcahue	0.32	0.51	0.69	E. Walker a C. Costa	0.51	0.76	0.72	Natales Sur	0.32	0.47	0.60
Quinchao	0.41	0.62	0.73	Cupquelan	0.43	0.63	0.56	Bahía tranquila	0.44	0.63	0.65
Queilen a Quellon	0.34	0.51	0.69	Quitralco	0.47	0.69	0.69	Seno Skyring	0.43	0.61	0.69
Quellon Sur	0.27	0.40	0.52	Fiordo Aysen	0.44	0.68	0.65	Campo Nevado	0.40	0.60	0.65
Chaiten al sur	0.35	0.54	0.60	Pto Aguirre	0.40	0.61	0.65	Córdova	0.38	0.60	0.65
Reñihue	0.36	0.56	0.69	Puyuhuapi	0.40	0.63	0.65	Xaultegua	0.42	0.63	0.65
Llancahue Comau	0.44	0.64	0.79	I. Magdalena-Melimoyu	0.56	0.80	0.86	Petite	0.34	0.55	0.65
								Isla Arrison	0.38	0.58	0.65
								Isla Prowse	0.33	0.50	0.56

Note: *Sensitivity* and *exposure* represent attributes of the RWB and values are as shown in Table 3. Risk = (*hazard* × *sensitivity* × *exposure*)/125.

[a]Hazard components used for Atlantic salmon were estimated as follows: indicator of stocked fish = 5 as the largest score corresponding to the largest number of fish/km^2. Indicator representing survival capacity away from cage = 3. Indicator representing trophic impact = 4. Indicator representing reproductive capacity = 3. The resulting value is the average of these four indicators (Table 1 and Table S2). Values for rainbow trout and for coho were calculated in a similar way (Tables S3 and S4, respectively).

resistance, hindering the survival and adaptation of escaped individuals when challenged by local conditions.[8] Although salmon species considered here show differences in their environmental requirements for spawning and early rearing life stages, the environmental susceptibility for their establishment is comparable.

Simulated large escapes of rainbow trout also generate high risks in many RWB in the Magallanes district (Table 4), and while the species is already there[29] we should not underestimate impacts from sturdier and fast growing strains selected for farming. Further, the simulation exercise (Table 4) can be used to assess risks of large escapes in any of the RWB and can inform on the risk components that must be evaluated before modifying the carrying capacity and production of any species or RWB.

4.3 | Risks engage both freshwater and marine ecosystems through the life cycle of anadromous salmonids

Since *Exposure* is high through many RWB, but especially in Los Lagos and Aysén districts (Tables 3 and 4), a relevant question is where are we likely to lose more biodiversity and ecosystem services? Unfortunately, there is not enough information to answer this question mainly because the indicators used to build the *exposure* index are only proxies and cannot sufficiently represent the goods and services that could be lost through direct or indirect effects of escaped salmon and their potential descendants (Table 1 and S8). Escaped salmonids could prey on pelagic fish and/or benthic organisms[12,26] but the magnitude of their impact is still unknown. Also, native fish that could be competitors and predators in the coastal marine areas such as *Trachurus* sp, *Merluccius* sp[12] and *Genypterus* sp have undergone significant overfishing leading to population declines during the past 30 years. A remaining question is whether salmonids could fill such a potential trophic empty space. In fact, artisanal fishers are sparingly catching escaped salmon and trout and possibly resident populations of the latter, in areas where they used to catch native species.[84]

An important information gap is the lack of datasets about biodiversity and uniqueness of freshwater ecosystems and transition zones in estuaries and watersheds that could be used by Atlantic and coho salmon for spawning and early rearing (Figures 4 and 5). Rainbow trout has an impact on native fish of rivers and lakes through predation, but specially through habitat displacement.[85,86] We could only assume that other salmonid species might have a similar impact, but as anadromous species they may have a much shorter residency time in freshwaters. Preliminary studies on the recently established Chinook salmon in southern Chile and Argentina support the later.[8,87] Yet, information on feeding and general habits of this species are scarce although recent studies suggest its diet as insectivorous[87] in freshwater environments, while individuals captured in coastal marine areas show empty stomachs suggesting their marine feeding takes place further offshore.[88] Atlantic and coho salmon may behave in a similar way.

5 | ADVANTAGES AND LIMITATIONS OF THE APPROACH

Our approach can be performed in data deficient situations even when biologically relevant information is limited since this can be generated from expert judgement from multiple disciplines and it can be improved through the process. The approach can guide targeted monitoring, which can feed back to improved risk assessments through improved scoring, also increasing certainty. Identification of the most relevant indicators is fundamental to customize each of the risk components describing *hazard*, *sensitivity* and *exposure*. Additional indicators can be added at any moment after broad discussions among experts and stakeholder could improve quality of information. Also, the relative relevance and weight of indicators and components can be revised. For example, we only included the number of individuals escaped, yet the risk to achieve spawning conditions as adults depends on other factors such as the life stage of the escaped individuals (juvenile versus adult). The incidence of escapes from marine farms occurs throughout the production cycle, and not enough data are available to account for the variability in the life stages of escapees. That is the reason for choosing a mid-point growth stage to estimate survival rates and trophic impacts. Specific information regarding sizes or ages of escapees should be included to improve risk assessments.

The use of this simple matrix provides an opportunity for adaptive management and collective identification of main information gaps based on current best available science. Therefore, the present risk assessment could be validated in the field and broader stakeholders' participation could be involved. An additional advantage of this approach is the generation of comparative risk levels among species which allow more focused monitoring and prioritization of RWBs. Also, some drastic actions can be adopted to reduce risks, including the reduction in farming production and the promotion of fishing pressure on escapes in areas of high risk. Because salmonid farming is the second most relevant non-mining export sector in Chile and it has relevant positive impacts on local development and employment in south of the country[24,25,49] these management actions would have relevant social and economic consequences and therefore they need to be carefully planned and periodical evaluations based on their effectiveness are needed.

An important gap in our analysis is that we do not consider differential *sensitivity* of RWB to extreme climatic conditions which are very often the main cause of escapes.[12,19] While most large escapes have been caused by extreme events (Figure 3) the existing information does not allow yet to assign an indicator for the likelihood of extreme events to all RWB. In fact, two of the largest escapes in the past 10 years have been caused by extreme winds such is the case in Reloncavi fjord,[26] but similar winds have caused small or no escapes in other RWB (Figure 3). This is further complicated by the fact that the intricate hilly geography and exposure to winds of fjords, inlets and sounds create very specific climatic and oceanographic conditions for every site. On the other hand, by using the cumulative number of escapees in each RWB as part of the hazard it is already reflecting those RWB that have had largest escapes due to extreme events of a similar nature (Table 1). Future improvements of the risk matrix and risk assessment should explore better indicators of local climatic conditions.

Among the limitations of our approach are those related to the level of certainty of the scoring in the absence of better available information (Tables 1 and 3). However, indicators with low certainty can help identify topics for further research and information priorities. For example, in the *hazard* generated by Atlantic salmon we assumed lower survival and ability to feed after escaping compared to the other species, based on available information from fishers and catch rates reported using gill nets in coastal areas.[8,12,28] However, it is possible that Atlantic salmon may use deeper areas, avoiding being caught by gill nets.[89] Thus, we could be underestimating the risk associated with escapes of this species. A counter argument is that if fish would be using deeper areas of fjords, they would be likely caught by the hake fishers, but this event has not been so far reported.

In this analysis, all indicators within each risk component have similar importance regardless of the quality and certainty level of each indicator. It is possible that the relevance of *exposure* could be much greater than that used here, but there is not enough ecological baseline information to evaluate and quantify the biodiversity of ecosystem services that could be lost due to salmonid escapes across large geographic areas of Aysén and Magallanes Districts. However, more information is developing,[42] and indicators should improve after risk components are evaluated with empirical information from the field.

Additional limitations of our approach include: (i) We do not address the temporal sequence of events, that is, 1. escape, 2. survival and feeding etc., 3. successful reproduction, 4. population expansion. Instead, we adopted a static picture of risk involving short term and long-term impacts. This issue could be addressed by updating and adjusting risk assessments frequently and eventually upon availability of better information and sequential models for each stage. (ii) We assume that available food is not a limiting factor for any of the species because we do not have direct information. However, several native top predators such as the Chilean jack mackerel and hake have been strongly overfished in the area[84] suggesting more of their food could be available for escaped salmonids. (iii) The boundaries of the RWBs could be a limitation because escaped fish might be able to move beyond such as the case described above for coho salmon.[76] This is possible considering that salmon can migrate larger distances in the open seas in the Northern Hemisphere and therefore broader geographical areas could be adopted in the future. (iv) The scoring scale (from 1 to 5) could be considered too coarse and perhaps can be expanded to contrast among relevant water bodies when more detailed field information is available.

Lastly, the ranking of risks we provide here must be considered as suitable mainly for comparative analysis and general reference for precautionary decision-making processes, given that the knowledge about both the geographic distribution of *exposure* indicators and the actual relationship between ecosystem *sensitivity* indicators is still incomplete.

6 | CONCLUSIONS AND RECOMMENDATIONS

Considering that Atlantic and coho salmon are not yet successful invaders in Chile, research attention is urgently needed to assess the environmental consequences of escapes of farmed individuals of these species. Given higher uncertainty in the estimation of some hazard and sensitivity components in the risks estimates reported here, it is necessary to focus research attention to their potential impacts in the field. This is especially relevant for Atlantic salmon considering the large number of individuals being farmed. This is also a priority considering strong public concern and increasing opposition to salmon farming especially in the Aysén and Magallanes districts.

Our findings can help to generate several immediate measures, aiming at field validation and further research to demonstrate harm produced by escapes. To do this, several steps are necessary: (i) development of a standardized monitoring protocol to assess presence of escaped salmon, especially in higher risk areas; (ii) development of a standardized monitoring protocol (e.g., eDNA) and a program to assess reproductive activities and presence of juveniles of Atlantic and coho salmon in some high 'sensitive to reproduction' streams and waterways; (iii) improve the ecological baseline information of the marine ecosystem where salmonid farming takes place and of watersheds that could likely host reproduction, and (iv) carry field assessment that allow resource managers to better describe and assess the fate and impacts of escaped salmonids. Such essential measures can assist in validating and improving the risk projections presented here and could facilitate more informed policies and specific regulations to reduce risks associated with salmon escapes. Precautionary measures could include reducing *hazard* by limiting or restricting overall production in RWB with high *sensitivity* and *exposure* ranks (Table 4), particularly within or near marine protected areas or other conservation areas. Special prevention and management measures or restrictions[5,15,16] can apply in areas with high biodiversity such as Llancahue–Comau, Chacao and Quinchao in Los Lagos, Magdalena-Melimoyu, Melchor–Isla Luz and Walker-Costa in Aysén, and Seno Skyring (Figure 1, Table 3). Many fjords and enclosed inner channels in Magallanes district are low risk now because the *hazard* is minor given comparatively low salmon production but if this would increase, risk would rise also because lower natural predation (sea lions) and fishing (Table 4).

The risk framework used here does not involve *adaptation capacity*, which together with *sensitivity* conform the vulnerability component in the risk equation (Equation (1)). Building adaptation capacity to reduce risks is essential and needs to be explored in the future. Some of the elements to consider to build adaptation and resiliency to face NNS impacts include better spatial planning of aquaculture, better reinforcement of regulations regarding safety measures of infrastructure to support extreme events, to address aging and wear of materials, to respond and mitigate escapes, etc.[15,16] Clearly, a potential prevention measure to reduce the risks associated with escapes is the reallocation of aquaculture facilities from highly vulnerable areas to other more suitable areas after adequately addressing social and production issues involved. The IUCN[90] recommends no high-density fish cage farming in areas with various ecosystem conservation categories including scientific purposes, preservation of wilderness, national parks and natural monuments. In other categories, the type of aquaculture to be allowed depends 'on whether the activity can be managed in such a way that it is compatible with the MPA's objectives'.[91] The intensive farming of NNS such as salmonids in Chile, might not be compatible with protected areas. Different authors have identified the Chilean Patagonia as a global natural reserve that needs to be protected against stressors, including salmonid farming.[73,92] Vila et al.[73] have proposed different conservation scenarios along the Tierra del Fuego islands in Chilean Patagonia to minimize the potential conflict between conservation and aquaculture. However, current information gaps and legal aspects including local level decision capacity prevent effective protection of these areas including against potential impacts of salmon farming. A long-term multi-sectoral marine spatial planning process[3] including a review of the current areas adequate for aquaculture might help to a better and more integrated use of the coastal zone. This could include the reallocation of farms, minimizing the conflicts and maximizing social and economic returns through different sustainable activities, including aquaculture. The current risk analysis offers new elements to explore and underscore those aspects that need more research and monitoring to inform policy decisions.

Unfortunately, explicit protocols to monitor aquaculture escapes and manage recapture are scarce, but see Dempster et al.[5] Monitoring the fate of escapes in receiving ecosystems is even less common and rarely implemented, however recent reports regarding the presence of tilapia and catfish in inland waters of China represent an important moving forward but also reveal a potentially risky situation for the conservation of biodiversity.[11] Society is starting to realize the costs of biological invasions, although the establishment of some NNS used in aquaculture have also shown social benefits such as food[10,93] and recreational and small-scale fisheries, regardless of which it is essential to offset the negative effects in the medium and long term.

Availability of relevant information including on species ecological and physiological characteristics, spatial distribution of farms, farms species and stocking, and escapee numbers as well as about sensitivity of recipient ecosystems is essential to develop good risk assessment and management. Therefore, aquaculture reporting at local, national, and often supranational levels is of great relevance to minimize environmental risks due to escapees and other impacts. Yet, the absence of information can be partially supplied by experts and sometimes by local or traditional knowledge to advance risk assessment and management. In the absence of sufficient information to establish impacts to biodiversity from NNS escapees, a risk assessment such as the one presented here can support the precautionary principle in policy making regarding aquaculture planning and management at local, national, and supranational scales.

AUTHOR CONTRIBUTIONS

Doris Soto: Conceptualization; formal analysis; investigation; methodology; supervision; validation; writing – original draft. **Ivan Arismendi:** Data curation; formal analysis; investigation; validation; writing – review and editing. **Andres Olivos:** Formal analysis; investigation; methodology; resources; software; validation. **Cristian Canales:** Formal analysis; investigation; methodology; resources; writing – review and editing. **Jorge Leon-Muñoz:** Formal analysis; investigation; validation; writing – review and editing. **Edwin J. Niklitschek:** Data curation; investigation; validation; writing – review and editing. **Maritza Sepulveda:** Data curation; investigation; validation; writing – review and editing. **Felipe Paredes:** Data curation; investigation; validation; writing – review and editing. **Daniel Gomez:** Investigation; validation; writing – review and editing. **Yuri Soria-Galvarro:** Data curation; formal analysis; resources; validation.

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CONFLICT OF INTEREST

DGU, CBCA and MS received funding from MOWI (salmon farming company) to study and follow up a massive escape of salmon in 2018, however the information provided by such study was only used as an additional reference in the present research to support information on artisanal fishing on escapes and trophic level position of escaped individuals (see cited report, Gomez-Uchida et al 2020).

DATA AVAILABILITY STATEMENT

The data base used to produce the risk estimations described in this manuscript is contained in full in the supplementary material provided here.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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