Non-native anadromous salmonids in the La Plata Basin: long distance colonization?

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Abstract

The introduction and dispersal of salmonids have been widespread in Patagonian basins, including anadromous species such as Chinook salmon (Oncorhynchus tshawytscha), rainbow trout or steelhead (O. mykiss), sea-run brown trout (Salmo trutta), and, to a lesser extent, coho salmon (Oncorhynchus kisutch). In recent years, Chinook salmon and steelhead have been reported in the Paraná and Uruguay rivers and in the estuary of La Plata River. This could be a result of long-distance movements, where stray individuals travel northward along the cold Malvinas current. They enter these rivers when it collides with the warm current originating from Brazil. However, this entry takes place within a specific timeframe when the water temperature remains below its lethal thermal threshold. Due to this temperature constraint and their reproductive characteristics, the introduction of salmonids into this basin would not present a risk to the native species. The projected impact of climate change, which anticipates an increase in river temperatures and a southward shift of the Brazilian current, would further support this hypothesis.

Key words: non-indigenous salmonids, Malvinas and Brazil current, Paraná, Uruguay and La Plata rivers

Introduction

Salmonids are non-native fish species in the southern hemisphere but they have been continuously introduced into cold temperate regions of South America, through escapes from fish farms and intentional stockings programs for sportfishing. The presence of salmonids in Argentina can be traced back to the first stockings carried out at the beginning of the 20th century in Patagonia (Baigún and Quiros 1985; Pascual et al. 2002). These programs resulted in the establishment of freshwater resident stocks comprising
mainly rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) and, to a lesser extent, brook trout (*Salvelinus fontinalis*), but failed to introduce typically anadromous stocks or species at that time (Baigún and Quiros 1985). The introduction of salmonids in Patagonia is controversial because, despite high social and economic value for recreational fishing (Pascual et al. 2009), several impacts on native fauna have been detected through direct predation and habitat displacement (Baigún et al. 2022). Currently, freshwater populations of rainbow, brown trout, and brook trout have been recorded beyond the Patagonia region, even in areas with suboptimal environmental conditions (high water temperatures, Carter 2005) for their establishment (Espínola et al. 2022).

Anadromous salmonids have also been found more recently in Argentina. In the Santa Cruz River (50°0.7’S; 68°2’W, Santa Cruz Province), Patagonia ecoregion, rainbow trout was probably introduced from the McCloud River, USA (Riva Rossi et al. 2004), showing either freshwater resident or anadromous life histories (Pascual et al. 2001). In addition, sea-run brown trout, derived from German domestic stocks of mixed origins (Valiente et al. 2007; Colihueque 2015) is found in the Gallegos (51°35’S; 68°59’W, Santa Cruz Province), the Grande (53°47’S; 67°4’W), Ewan (54°0.6’S; 67°9.9’W, San Pablo (54°16’S; 66°44’W) and Irigoyen (54°31’S, 66°17’W) rivers in Tierra del Fuego Province and more recently in the Santa Cruz River (Santa Cruz Province) (Casalinuovo et al. 2018; Baigún et al. 2022). The typically anadromous Chinook salmon is, however, much more widespread across the Argentinean and Chilean Patagonia (Correa and Gross 2008; Figueroa-Muñoz, et al. 2023). In the Argentinean Patagonia, this species has invaded rivers flowing towards the Pacific coast (Di Prinzio and Pascual 2008), small tributaries of the Santa Cruz basin (Ciancio et al. 2005), and streams draining the south of Tierra del Fuego Island (Fernandez et al. 2010; Nardi et al. 2019). The invasion of Chinook salmon in those ecosystems is attributed to feral populations that have migrated from rivers of south Chile (Riva Rossi et al. 2012; Ciancio et al. 2015; Di Prinzio et al. 2015).

Recently, a single Chinook salmon was found in the Paraná River Delta, in the lower La Plata River, on the Atlantic coast of Argentina (Liotta 2019). In addition, further anecdotal reports of salmonid catches by local recreational and artisanal fishermen have stressed the potential of anadromous salmonids to invade the La Plata River. In this context, our study offers an updated review of the records of captured salmonids in Argentina, specifically outside the Patagonian ecoregion and particularly within the La Plata River basin. Our primary focus in this study is to describe novel reports of salmonid species never previously registered in this basin, which may be indicative of an ongoing population expansion. We also discuss the potential dispersal mechanisms and the risks that these species may pose to the native fish assemblages.
Materials and methods

The La Plata Basin accounts for 17% of the surface area of the South American continent and is the fifth largest river basin in the world, extending over 3,100,000 km². The average annual temperature varies from 13 °C to over 25 °C from the south to the north, respectively. In the central region, the annual temperature exhibits a fluctuation of approximately 12 °C. In winter (June, July, and August), the temperature gradient from north to south varies between 20 °C and 8 °C respectively. In summer (December, January and February) the northwest of Argentina exceeds 28 °C, while the coastal areas of Brazil and Uruguay reach 23 °C. Regarding the transition seasons, spring (September, October, and November) is warmer than autumn (March, April and May, Barros et al. 2006). The La Plata Basin covers an extensive part of central and northern Argentina, southeast Bolivia, almost all the southern part of Brazil, the whole of Paraguay and a large part of Uruguay. The basin is formed by the Paraná, Paraguay and Uruguay rivers systems and the La Plata sub-basin itself, with the Paraná River system being the most extensive. These rivers make up the ecoregions called the Lower Paraná and Lower Uruguay (Abell et al. 2008). The lower Paraná forms a large subtemperate alluvial plain, free of dams, where most ecological processes are driven by flood (November-March) – drought (August and October) cycles. This ecoregion is characterized by a great heterogeneity of habitats and a diverse biota adapted to the great spatio-temporal heterogeneity. The Paraná River has an average flow of 15,000–17,000 m³/s. In winter (June, August and July), the average minimum flow is 13,842 m³/s with an average minimum temperature of 10 °C. The average maximum flow in summer (December, January and February) is 15,773 m³/s with an average maximum temperature of 32 °C (Giacosa et al. 2020). The Lower Uruguay ecoregion includes the middle and lower Uruguay River, which with the confluence of the Paraná River forms the estuary of La Plata River. In turn the Uruguay river presents a flow of 45,000 m³/s. Average temperature in winter is 16 °C and 25 °C in summer.

Data collection and identification

First, a literature search, using “salmon” and “Argentina” as keywords, was performed on scientific (Web of Science, Scopus, Google scholar) and non-scientific (Google, electronic newspapers and fishing magazines) databases until 31st December 2022. All scientific and non-scientific reports were checked for the occurrence of salmonids outside the Patagonia region and reported if they provided reliable evidence of a salmonid record. Artisanal and recreational fishermen were kindly invited to send pictures of the salmonid caught, together with data on fish size and weight, fishing gear, and the location of the capture. All the data sent on salmonids captured between 2020 and 2021 were initially checked for veracity and accuracy through...
Table 1. Estimated total length, weight and sex data of non-native salmonids captured in the Lower Paraná and Uruguay ecoregions. BA = Buenos Aires; ER = Entre Ríos; and SF = Santa Fe Tl = total length; F = Female. The first record of each species is typed in bold.

<table>
<thead>
<tr>
<th>Code</th>
<th>Date</th>
<th>Localization</th>
<th>River</th>
<th>Latitude - longitude</th>
<th>Species</th>
<th>Tl (cm)</th>
<th>Weight (g)</th>
<th>Sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>24/10/2018</td>
<td>San Pedro, BA</td>
<td>Paraná</td>
<td>−33.083333° : −33.083333°</td>
<td><em>O. tshawytscha</em></td>
<td>72.3</td>
<td>4,500</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>26/09/2020</td>
<td>Concepción del Uruguay, ER</td>
<td>Uruguay</td>
<td>−32.466667° : −58.233333°</td>
<td><em>O. tshawytscha</em></td>
<td>70</td>
<td>5,000</td>
<td>?</td>
</tr>
<tr>
<td>3</td>
<td>17/10/2020</td>
<td>Concepción del Uruguay, ER</td>
<td>Uruguay</td>
<td>−32.466667° : −58.233333°</td>
<td><em>O. tshawytscha</em></td>
<td>60</td>
<td>4,000</td>
<td>?</td>
</tr>
<tr>
<td>4</td>
<td>15/09/2021</td>
<td>Hudson, BA</td>
<td>La Plata</td>
<td>−34.733333° : −58.133333°</td>
<td><em>O. mykiss</em></td>
<td>60</td>
<td>4,700</td>
<td>F</td>
</tr>
<tr>
<td>5</td>
<td>04/11/2022</td>
<td>Arroyo Seco, SF</td>
<td>Paraná</td>
<td>−33.150000° : −60.433333°</td>
<td><em>O. tshawytscha</em></td>
<td>65</td>
<td>5,260</td>
<td>F</td>
</tr>
<tr>
<td>6</td>
<td>14/11/2022</td>
<td>Arroyo Seco, SF</td>
<td>Paraná</td>
<td>−33.150000° : −60.433333°</td>
<td><em>O. tshawytscha</em></td>
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<td>11,760</td>
<td>F</td>
</tr>
<tr>
<td>7</td>
<td>25/09/2023</td>
<td>General Lagos, SF</td>
<td>Paraná</td>
<td>−33.083333° : −60.533333°</td>
<td><em>O. tshawytscha</em></td>
<td>100</td>
<td>11,000</td>
<td>?</td>
</tr>
</tbody>
</table>

*See Liotta (2019)*

Results

From 2020 to 2023, seven individuals corresponding to two species of the genus *Oncorhynchus*, *O. tshawytscha* (six specimens) and *O. mykiss* (one specimen), were caught outside the Patagonia region, in systems belonging to the La Plata River basin (Figure 1; Table 1).

In the Paraná River, the first record of *Oncorhynchus tshawytscha* occurred in the delta of this river (Lower Paraná ecoregion). It was captured in Buenos Aires Province, San Pedro, in the Paraná River main course near the mouth of San Pedro creek, 33°37'S; 059°45'W. The second and third reports occurred on September 26th and October 17th of 2020, respectively (Figures 2a and 2b). Both individuals were captured in the vicinity of the city of Concepción del Uruguay in the Uruguay River (Lower Uruguay ecoregion). One specimen of *Oncorhynchus mykiss* was captured for the first time in September 2020 at the Hudson area, in the de La Plata River (province of Buenos Aires, Figure 3). Two individuals of *O. tshawytscha* (Figure 4) were captured between November 4th (Figure 4a, b), and 14th of 2022 Figure 4c, b), in the Santa Fe Province. Both records were in the main course of the Paraná River, near Arroyo Seco, close to Rosario a city. Finally, an individual of this species was captured in the province of Santa Fe, on September 25th, 2023. It also occurred on the main channel of
the Paraná River, near to the city General Lagos, located between the cities of Arroyo Seco and Rosario (Figure 5).

Except for the first and sixth individual shown in Table 1, weight and size estimates correspond to fishermen’s observations.

Discussion

Initial colonization, local establishment and subsequent spread of a non-native species into a new area is fundamental for a successful invasion process. The success of an invasion depends on the biological attributes of the non-native species as well as the ecological characteristics (biota and environment) of the invaded environment (Colautti et al. 2006). This process can be favored by human-mediated repeated introductions (propagule pressure, Colautti et al. 2006) as it is the case of the aquaculture of non-native fish (Casal 2006).
Figure 2. Second and third record of *Oncorhynchus tshawytscha*. (a) captured in September and (b) October 2020 on the Uruguay river. The Chinook salmon of 2a resembles a male showing sexual dimorphic traits associated with the reproductive period, such as pink coloration on its belly, incipient curvature of jaws and snout, and hump formation. Photographs by Fabio Baena and Pablo Foldesi.

Figure 3. First record of a mature female of rainbow trout *Oncorhynchus mykiss* captured in September 2021 (a) and (b) in the La Plata River; (c) Zoom on mature eggs found in one of the ovaries. Photographs by Wilmar Merino.
Figure 4. Fourth and fifth record of *O. tshawytscha* in the Paraná River. (a) teeth in the lower jaw and (b) maturing eggs of *Oncorhynchus tshawytscha* captured on November 4th of 2022; (c) and (d) Female of *O. tshawytscha* captured on November 14th of 2022. Photographs by https://m.facebook.com/p/Rios-Sanos-100041376166542/
Anadromous salmonids are non-native to Argentina, but they have been introduced for sport and aquaculture purposes across Patagonia during the first decades of the 20th century or have naturally propagated from Chile since the 1980s. Since then, they have rapidly spread and colonized numerous Atlantic and Pacific basins throughout Patagonia (Di Prinzio and Pascual 2008). In Patagonia, the steelhead, the anadromous ecotype of the rainbow trout, has only been reported for the Santa Cruz River, thus suggesting that the specimen captured in the La Plata River estuary would correspond to a stray individual from this population, representing the first record of this.
Figure 6. Distributions of anadromous salmonids and their relationship with marine currents. Inside the red square the recent records are depicted.

species in a basin located at a latitude so far north. Previously, the highest latitude at which straying steelheads had been found was in the coast of Negro River province, where an individual from the Santa Cruz River was caught in the nearby of the Negro River mouth in January 2000 (Pascual et al. 2001). In the case of the Chinook salmon, the increase in its records reflects the spread of this species across the Patagonian rivers, where adult specimens of established self-sustaining populations might be colonizing other rivers and streams (Baigún et al. 2022). Currently, the most conspicuous Chinook salmon populations are located in the Santa Cruz River basin, where self-sustaining spring runs of this species have colonized different tributaries in the upper basin that have favorable conditions for reproduction (Ciancio et al. 2015).

The presence of anadromous salmonids in the La Plata River, however, appears to be a typical case of straying, where individuals that have failed to reach their home, natal streams for breeding, disperse to other streams, thus expanding their distribution range (Keefer and Caudill 2014). This phenomenon may be attributed to the long-distance movement of individuals that travel northward along the marine corridor driven by the Malvinas current, which transport cold (< 7 °C), low-salinity water northward from the subpolar South Atlantic into the subtropical South Atlantic (Piola et al. 2000; Figure 6). The Malvinas current collides with the warm-salty (up to
26 °C) poleward flowing Brazil current at about 38° S, forming the Brazil-Malvinas Confluence (Combes and Matano 2014). This confluence is characterized by warm- and cold- meanders, eddies and water fronts (water temperature can fluctuate from 0 °C to over 25 °C; 14–16 °C during winter and early spring months, Combes and Matano 201), that induce strong interactions between the shelf and the deep ocean, generating intense cross-shelf exchanges, that have important consequences for marine life, as they provide nutrients to the oligotrophic deep ocean from organisms that live on the shelf (Manta et al. 2022). A distinct characteristic of this confluence is the effect of the discharge of the La Plata River estuary, which provides freshwater, suspended sediment, nutrients, and pollutants to the neighboring shelf waters (Piola et al. 2000). The waters of the La Plata River plume, of considerably low salinity, spread northward over the coastal shelf and are exported to the open ocean (e.g., Guerrero et al. 2014).

This hypothesis is consistent with Ciancio et al. (2010) who suggested that considering the distribution of sea-surface water temperatures and prey distributions, the entire Patagonian shelf and up to the slope boundary constitute potential areas of distribution of Chinook salmon and steelhead. Both, nearby and long-distance dispersal, resulting from straying appear to be crucial for the early spread and colonization of non-native Chinook salmon across several non-native environments (Quinn et al. 2001; Correa and Gross 2008; Gomez-Uchida et al. 2018). Both homing (the tendency to return to the natal stream for breeding) and straying rates exhibit substantial variation among salmon populations (Quinn 1993). Homing rates for native salmon species can reach up to 99% (Ford et al. 2012). In fact, it has been documented that introduced, non-native populations tend to stray more than both native salmon and hatchery stocks reared and released on-site (Quinn 1993; Jonsson et al. 2003). Of particular interest are non-native populations originating from introductions, such as in New Zealand, where straying rates vary between 4 and 20% (Unwin and Quinn 1993). While most strays occur near natal areas, long-distance straying also occurs, especially in hatchery populations introduced or transported as juveniles (Keefer and Caudill 2014). Quinn (1993) suggested that straying may be more frequent when salmon densities are low, which could be applied to the Patagonian Chinook populations found only in few small rivers in Tierra del Fuego and the Santa Cruz River, where spawning take place exclusively in the upper basin’ small rivers with limited spawning grounds.

However, a smaller fraction of the population strays and breeds in non-natal areas, enabling them to colonize new basins (Keefer and Caudill 2013). Therefore, the presence of salmonids in this basin could be attributed to migrant individuals dispersing in search of prey across the Malvinas current and the Patagonian shelf. When they encounter the low salinity nutrient-rich waters of La Plata River plume at the Brazil-Malvinas Confluence zone, they move towards the continent aiming to enter this basin to reproduce.
Figure 7. Thermal regime of maximum and minimum water temperature recorded from 2008 to 2019 at Nueva Palmira (see location in Figure 5). Critical threshold values for: 1) Chinook migration; 2) steelhead migration; 3) Lethal temperature for adults of steelhead; 4) lethal conditions for eggs and embryos of Chinook; 5) Lethal conditions for eggs and embryos of steelhead; 6) Lethal temperature to adults of Chinook. The grey rectangle indicates the time window of entry into the La Plata River of chinook, while the black line indicates the steelhead record. Data from Carter (2005).

It is interesting to note that the timeframe during which salmonids were caught into La Plata and Uruguay rivers coincided with the spring season (Table 1, Figure 7). This entrance corresponds with the time period when the Chinook salmon spring run initiates their upstream migration from the ocean and into the Santa Cruz River. The significant influence of large-scale dominant currents, such as the Malvinas current, also account for the presence of anadromous salmon along the Brazilian coast. Apart from the coho salmon (TL:76.1; 2,788 gr and Male), which was detected in 2002 at the Lagoa dos Patos estuary, this species was also reported in the area of Bombinhas (Santa Catarina Brazil) 1,100 km north of the confluence of the Malvinas and Brazil currents (Soto and Rocha 2022).

While the expansion of Chinook salmon in South America appears to be an ongoing process (Correa and Gross 2008; Gómez-Uchida et al. 2018, Figueroa-Muñoz et al. 2023), the potential of this species to become invasive in the La Plata Basin appears to be minimal (Liotta 2019). Adult salmonids migrating upstream for breeding exhibit specific habitat requirements and operate during specific time windows to ensure successful reproductive migration and spawning. For instance, streams that are excessively warm may impede or pose delays in upstream migration, rendering them unsuitable for reproduction and egg survival. Thermal conditions of the Paraná and Uruguay rivers are not suitable for salmonid reproduction. Moreover, the water temperature of these rivers would not be adequate for the persistence of salmonids beyond the delta of the Paraná River and in the lower Uruguay
River, and only during a brief time window, up to October and November, and as long as the water temperature remains below 25 °C (Figure 7). Salmonids also require clear and relatively fast- waters with gravel-dominated substrates to migrate upstream and build nests (Bjornn and Reiser 1991). However, the water quality, velocity and substrate composition of the Paraná and Uruguay river basin would not be favorable either, as it they are characterized by slow, sluggish currents, fine-substrate with elevated suspended silt and clay (Amsler and Prendes 2000). Furthermore, the potential impact of these anadromous salmonids on the native fauna appears to be insignificant.

Given that salmonids are species known for constructing nests, the risk of competition with native species for spawning habitats remains low, primarily due to a substantial proportion of fish species in the La Plata River being free spawners (Agostinho et al. 2004). Furthermore, anadromous salmonids, regardless of being semelparous or iteroparous, do not feed during their reproductive migrations, as they have developed an intense trophic phase in the sea. Consequently, any direct predation impacts on native species are not anticipated. In the eventuality that these individuals were to reproduce, their juveniles might indeed exert an ecological impact (competition for preferred habitat, Vargas et al. 2010), as happens in so many Patagonian rivers. In fact, the primary impacts of salmonids are usually attributed to their juvenile stage when they compete with both native and non-native species for food and habitat (Macchi and Vigliano 2014, Di Prinzio and Arismendi 2018). Moreover, the anticipated climate change within the basin (e.g. Barros et al. 2005) and the increasing advance of warm waters from the Brazil current towards the Patagonian shelf in recent years (Chidichimo et al. 2022) would also serve to curtail the potential invasion of salmonids in the future.

In summary, we conclude that the presence of anadromous salmonids in the temperate waters of the La Plata River is an occasional phenomenon that has been previously recorded for other Patagonian anadromous species in the past, such as the Patagonian lamprey (Geotria macrostoma, Riva Rossi et al. 2020) and the Patagonian blennie (Eleginops maclovinus, González-Castro et al. 2013). Given the scale of these movements, it is plausible that these occurrences involve stray specimens carried by the Malvinas cold current. However, over the last three decades, there has been a consistent increase in sea surface temperatures across the Southwestern Atlantic Ocean. This warming trend is accompanied by a rise in the frequency, duration and intensity of positive sea surface temperature anomalies (Ortega et al. 2016). Due to the projected temperature elevation in the La Plata basin and the broader Atlantic Ocean, the risk of dispersal and invasion of anadromous salmonids from more temperate basins will likely be constrained. Consequently, concerns about anadromous salmonids posing a serious threat to native species should be minimized. Nonetheless, conducting further assessments of new captures and records is imperative to confirm the migration routes of these species.
Non-native salmonids in the La Plata River basin

Authors’ contribution
LAE, CB and LNS Conceptualization, Methodology, Writing – Original Draft. CRR, PQ and CDP Review and Editing and provided specific information on the life strategy of the salmonids. EA, APR and MCMB, Formal analysis, Review and Editing and provided useful insight into the structuring of the manuscript. All authors contributed and approved the final version of this letter.

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