Biol Invasions
DOI 10.1007/s10530-010-9731-x

INVASION NOTE

Chinook salmon (*Oncorhynchus tshawytscha*, Walbaum 1792) in the Beagle Channel, Tierra del Fuego: the onset of an invasion

Daniel Alfredo Fernández · Javier Ciancio · Santiago Guillermo Ceballos · Carla Riva-Rossi · Miguel Alberto Pascual

Received: 25 June 2009 / Accepted: 22 February 2010

Abstract In this paper we provide the first report of the presence of exotic Chinook salmon (*Oncorhynchus tshawytscha*) in two rivers off the Beagle Channel, Lapataia and Ovando, in southern Tierra del Fuego. We also confirm that successful reproduction occurred in the fall of 2007, as we captured yearlings in freshwater. Scale pattern analyses of adult fish caught were all of the "stream" ecotype, with ages ranging between 3 and 5 (average 4.2 year). Stable isotope analysis of Ovando-Lapataia Chinook population indicates general patterns consistent with those of other populations in the region, but characteristically enriched levels of C indicates a distinct ocean feeding location as compared to Atlantic populations in the Santa Cruz River. Two different haplotypes, one identical to the unique haplotype of the Caterina River population, were found in the Ovando-Lapataia rivers, providing partial evidence for some level of contemporary segregation between these two populations. As an exotic species, Chinook salmon have been able to use the ocean as a waterway to rapidly colonize new habitats both in New Zealand and in several Pacific and Atlantic river basins of continental Patagonia. This record expands the known distribution of this species in Patagonia further south and into the Island of Tierra del Fuego. Its presence in the Beagle Channel creates the conditions for its expansion to a significant collection of new rivers, as well as to adjacent marine areas in and around the Southern Fuegian Channels. Our results provide support to the idea that, in practice, no district of Patagonia is sheltered from the colonization by invasive anadromous Salmonids.

Keywords Chinook salmon · Beagle Channel · Patagonia · Exotic anadromous salmon

D. A. Fernández (✉) · S. G. Ceballos
Austral Center of Scientific Research (CADIC-CONICET), 200 Bernardo Houssay, Ushuaia, Argentina
e-mail: dfernandez@cadic.gov.ar; dfernandez.ush@gmail.com

J. Ciancio · C. Riva-Rossi · M. A. Pascual
Centro Nacional Patagónico (CENPAT-CONICET), 3500 Blvd Brown, Puerto Madryn, Chubut 9120, Argentina

M. A. Pascual
Universidad Nacional de la Patagonia SJB, Sede Puerto Madryn, Chubut, Argentina

Introduction

The introduction of salmonids in Patagonia (37°–55°S) began early in the twentieth century, with fish imported from North America and Europe. Today, salmonids inhabit practically every river basin of the region, with rainbow (*Oncorhynchus mykiss*), brown (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*) being the most widespread species (Pascual et al. 2002). In Tierra del Fuego the introduction started in 1931 and included brook, brown, and

Published online: 07 March 2010

rainbow trout, as well as landlocked salmon (*Salmo salar sebago*) and, more recently, the Atlantic salmon (*Salmo salar*).

In recent years, it has become evident that anadromous populations of salmonids—those that perform a migration to the ocean during their life cycle—have been particularly successful at colonizing rivers of Patagonia, as compared to other regions of the World (Pascual and Ciancio 2007). Exotic anadromous salmonids constitute a novel threat to regional aquatic resources: their effects can project to both the ocean and rivers, and they are not necessarily confined to particular river basins, but have the ability to quickly colonize new ones. In Patagonia, anadromous populations of brown trout are found in Atlantic rivers, both in the continent (Río Gallegos) and in the Island of Tierra del Fuego (Rio Grande, Ewan, and others). Anadromous rainbow trout inhabit at least one river in continental Patagonia (the Santa Cruz River, Pascual et al. 2001). Chinook salmon (*Oncorhynchus tshawytscha*) have been particularly successful at establishing anadromous populations in both Pacific and Atlantic river basins of continental Patagonia (Ciancio et al. 2005; Correa and Gross 2008; Di Prinzio and Pascual 2008; Soto et al. 2007), from the Pilmaiquen drainage in Chile (40°37′S) southward to the Strait of Magellan and in the Atlantic up to the Caterina River in the Santa Cruz River Basin of Argentina on the Atlantic Ocean (50°S). Molecular techniques have indicated that Chinook salmon actively colonized Atlantic rivers from Pacific locations (Becker et al. 2007). To date, however, this species had not been reported in rivers of the Island of Tierra del Fuego, although its ocean shores were certainly exposed to migrating Chinook salmon.

In this paper, we present the first record of Chinook salmon in rivers flowing into the Beagle Channel, in southern Tierra del Fuego. We report on Chinook ecotypes, ages, stable isotope signatures, DNA haplotypes and compare the Ovando-Lapataia population with the Caterina population (Santa Cruz Province). We also report a successful reproductive event of this population which might constitute the onset of an invasion. Implications of this colonization are briefly discussed.

Materials and methods

The Tierra del Fuego National Park, located in the SW of the Argentinean portion of Tierra del Fuego, has an area of 63,000 ha (Fig. 1). Within the park, the Lapataia and Ovando rivers drain the water of Roca Lake, which spans across the border with Chile, into the Beagle Channel (3 km from the lake to the sea). Historical river flows at the mouth of Roca Lake,

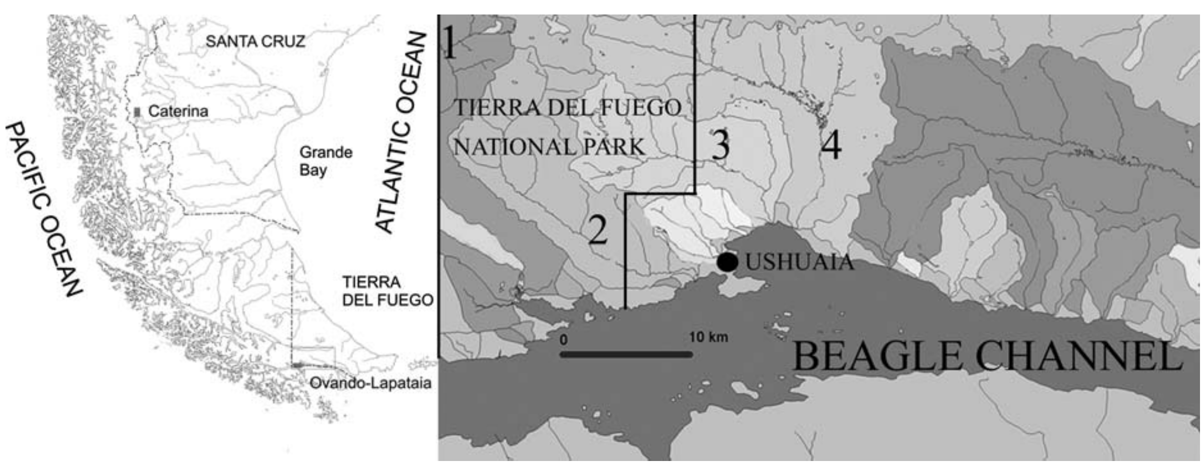

Fig. 1 (*Left*) Map of Southern South America showing the location of Caterina River and Ovando-Lapataia River. The dark rectangle is reproduced enlarged on the right. (*Right*) Map of the Beagle Channel in the vicinity of the Tierra del Fuego National Park, showing the location of the different river basins susceptible of invasion by Chinook salmon. The area and average flow of the principal river basins numbered from west to east are *1* Ovando-Lapataia: 56,434 ha and 20 m^3/s, *2* Pipo: 15,269 ha and 4.01 m^3/s, *3* Arroyo Grande: 12,364 ha and 3.25 m^3/s, *4* Olivia: 20,562 ha and 5.40 m^3/s, *5* Lasifashaj: 42,618 ha and 11.19 m^3/s, *6* Varela: 16,612 ha and 4.4 m^3/s and *7* Cambaceres: 16,008 ha and 4.20 m^3/s

where both rivers start were 17.4 m^3/s in 1985–1986 and 20.01 m^3/s in 1986–1987, the greatest river flow in the vicinity of Ushuaia city.

In April 2006 we received reports from park rangers, who noticed large fish spawning in a shallow gravel section of the Ovando River. Two of those fish were captured by fishermen in the Lapataia River. We analyzed pictures of both fish, taken at the time of harvest, and the head and tail of one of them that was provided to us for inspection, concluding they were Chinook salmon.

Based on these reports, we conducted field surveys in April 2007 catching 10 adult Chinook salmon with gillnets. We removed scales from all individuals, from an area located below the anterior margin of the dorsal fin, approximately five scale rows above the lateral line. We cleaned three scales of each fish, made impressions on acetate cards and inspected them on a microfiche reader. We used the abrupt change from narrowly spaced *circuli* near the scale focus or center to wider spaced *circuli* formed during growth in the ocean to separate the freshwater nucleus from marine growth zones. We classified individual fish as "stream" or "ocean" type (Healey 1991) based on criteria for the pattern of *circuli* in the freshwater nucleus developed by (Koo and Isarankura 1967) for North American Chinook salmon and applied by (Unwin and Lucas 1993) to the species in New Zealand. We considered a freshwater growth zone with few and relatively wide *circuli* that did not contain a slow-growth check as an ocean-type freshwater nucleus, and an area of many *circuli* including a distinct narrow band of more closely spaced *circuli* near the outer border as a stream type freshwater nucleus. As a supplementary criterion to make the ocean/stream distinction, we counted *circuli* within the freshwater growth zone on the screen of a microfiche reader. We measured the radius of the freshwater nucleus along the anterior–posterior axis of the scale on digital pictures processed with the aid of an image analysis software (ImageJ, http://rsb.info.nih.gov/ij/index.html, NIH, USA), and a custom-made MS Excel macro. We also identified ocean *annuli* and counted them on the microfiche reader, but since significant resorption was apparent we used this data only as an estimate of minimum ocean age.

We conducted C and N stable isotope analysis on 10 fish collected in the Ovando-Lapataia river and compared the observed isotope signatures with those of Chinook salmon from the Caterina River in the Santa Cruz River Basin, and from fish captured incidentally on bottom trawlers in the Bahia Grande area (42°–52°S) (Ciancio et al. 2005). Dorsal muscle was removed from all fish and tissues were stored frozen for transporting to the lab, where all samples were dried at 60°C for 48 h, ground to a fine powder, and sent for analysis of carbon and nitrogen content and stable isotope signatures (Stable Isotope Facility, University of California, Davis). The stable isotope ratios are expressed as δ values as: $\delta X = [(Rsample/Rstandard)1] \times 1{,}000$ where X is ^{13}C or ^{15}N and R the corresponding ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$. Standards used were Vienna Pee Dee belemnite for C and N_2 for N.

Total genomic DNA was extracted from fin clips preserved in 70% ethanol with a standard phenol–chloroform extraction protocol (Sambrook and Russell 2001). We used primers S-phe and P2 and the PCR protocol of Nielsen et al. (1994a) to amplify a highly variable segment of salmonid mitochondrial DNA (mtDNA), including 188 base pairs (bp) of the control region and 5 bp of the adjacent phenylalanine gene. We compared the mtDNA sequences obtained in this study with Chinook salmon haplotypes from California (Nielsen 1998) and New Zealand (Quinn et al. 1996), and to those reported by Becker et al. (2007) for fish sampled at the University of Washington Hatchery and the Caterina River in Patagonia in order to establish the possible origin of the invaders.

Results

In 2007 we located 10 redds (in three different areas) of about 1 m in diameter and 50 cm depth in the Ovando and Lapataia rivers (Fig. 1). Between March 23 and May 15 we captured 10 Chinook salmon (1 male, 9 females; 85–100 cm; 7.5–12 kg, Table 1). The minimum average age was estimated at 4.2 years (range 3–5) from scale analysis (Table 1).

All 10 spawners collected in 2007 showed a freshwater growth consistent with a stream type ecotype. The average number of *circuli* in fresh water was 19.2 and the average radius 442 µm. The relationship between number of *circuli* and freshwater nuclei radius for Ovando-Lapataia fish had a lower slope than that observed for stream type fish from the Caterina river (Fig. 2; $11.5 < 25.8$, test of homogeneity of slopes, $P = 0.004$).

Table 1 Details of the fish caught in the Ovando-Lapataia river in 2007

Date	No.	Sex	Fork length (cm)	Standard length (cm)	Weight (kg)	Age (years)	Freshwater	
							No. of Circuli	Radius (μm)
03/23/2007	1	Male	100.0	–	10.0	4	11	378
03/23/2007	2	Female	88.8	79.0	9.2	4	22	440
03/23/2007	3	Female	87.0	76.0	7.6	4.5	19	420
03/23/2007	4	Female	95.5	85.5	10.80	4.5	24	513
03/23/2007	5	Female	94.0	84.0	11.4	4	18	404
03/23/2007	6	Female	95.0	85.0	12.0	5	17	436
03/29/2007	7	Female	85.0	76.0	7.5	5	13	367
04/02/2007	8	Female	89.0	79.0	7.5	4	26	538
04/02/2007	9	Female	90.0	81.0	8.9	3.5	21	536
05/16/2007	10	Female	–	80.0	7.1	4	21	482

All the fish were of the stream ecotype

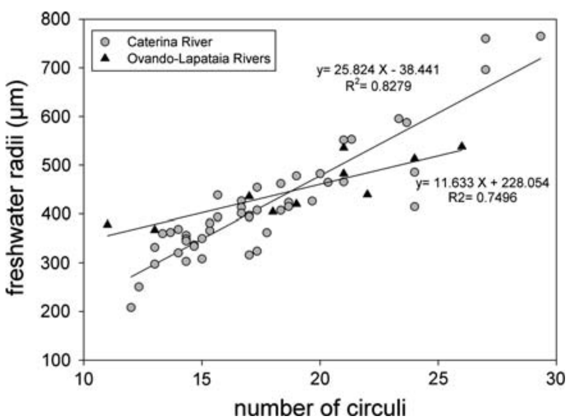

Fig. 2 Scales radii vs circuli number for the Caterina River population (*gray circles* are stream type and open circles are ocean type) and the Ovando River population (*black triangles*). Significantly different regression lines built using only stream type salmon populations

Spawning fish from the Caterina River are enriched in both N and C stable isotopes with respect to ocean fish, an expected and well documented outcome of the prolonged fasting characteristic of salmonids prior to spawning (Doucett et al. 1999). Nitrogen isotope signatures ($\delta\ ^{15}N$) of Ovando fish are not different from those of ocean bound Caterina River fish (*t*-test, $P = 0.5$) and lower than those of the Caterina River fish (*t*-test, $P < 0.001$). Meanwhile, the C signature of Ovando fish is enriched with respect to both other groups. (*t*-test, $P < 0.001$).

Two mtDNA haplotypes were recovered in eight fish sequenced from the Ovando-Lapataia Rivers. The 188 bp control region segment that we sequenced showed no new base substitutions when compared with Chinook salmon mtDNA haplotypes previously reported (e.g., Nielsen 1998). The Ovando-Lapataia sample was dominated by mtDNA haplotypes “WA1” and “SC”, identified by Becker et al. (2007) in Chinook Salmon from the Caterina River and the University of Washington Hatchery, respectively (Genebank accession numbers EF531711 and EF-531713), represented in six fish. The second haplotype, recovered in the two remaining fish, was equivalent to the mtDNA haplotype TSA3, identified by Nielsen (1998) in Chinook salmon populations from the Sacramento River in California, and by Quinn et al. (1996) in Chinook salmon introduced into New Zealand from California, but absent in Caterina River fish (Mezga 2009).

During beach seines fishing in 2007 and 2008 we caught a parr (October 31, 2007) and three smolts (April 3–15 2008) in the Lapataia and Ovando Rivers.

Discussion

We provide the first report of the presence of Chinook salmon in a river flowing into the Beagle Channel, during the characteristic spawning time of the species in the region (March–April). The subsequent capture of juvenile fish in the same sites offers concrete evidence of successful reproduction in these rivers, substantiating a further step in the effective colonization of these rivers by Chinook salmon. All the adults caught in the site were *stream* *type* fish, a pattern consistent with the presence of yearlings the following year.

Diverse factors could determine the existence of ocean or stream ecotypes in Chinook salmon populations, productivity and distance to the sea being the best documented (Healey 1991). These two characteristics coexist on the Pacific Coast of North America. At low latitudes (California) the rivers have high productivity and the spawning sites are close to the sea, both characteristics favoring marine ecotypes. At high latitudes (Alaska) the rivers have lower productivity and the spawning sites are far away from the sea, favoring a stream life history. The ecotype of the ancestors could also be a factor, but not a definitive one since both stream and ocean ecotypes arise from original stream-type populations in New Zealand (Quinn et al. 2001). The fact that all Chinook fish observed in the Ovando River belonged to the stream ecotype is in agreement with the low productivity hypothesis.

Both stable isotope concentrations are enriched along the marine food web (3.4‰ δ ^{15}N and 0.8‰ δ ^{13}C) (Van Der Zanden and Rasmussen 2001), and are also enriched during fasting of fish (Doucett et al. 1999). Because of low enrichment ratio of δ ^{13}C, this isotope has been used as tracer of C sources or feeding areas (Michener and Schell 1994). Anadromous salmon are typically enriched with δ^{15}N and δ^{13}C relative to the other sources of N and C in watersheds (Rubenstein & Hobson 2004), revealing ocean migrations in individuals sampled in freshwater. C signatures also correlate with the use of different ocean domains by different populations (Ciancio et al. 2008). Stable isotope analysis of Ovando-Lapataia Chinook population indicates general patterns consistent with those of other populations in the region, but characteristically enriched levels of C indicates a distinct ocean feeding location as compared to Atlantic populations in the Santa Cruz River. The absence of a fasting effect on δ^{15}N of Ovando-Lapataia fish compared to Caterina River fish could be due to the low cost of less than 3 km river migration in the former population.

DNA analysis indicates that Caterina and Ovando populations may have different parental sources. Whereas Caterina fish are monomorphic, likely resulting from founder events occurring during the colonization of this river, a second haplotype was found in the Ovando-Lapataia. In any event, the presence of an alternative haplotype in new populations in Tierra del Fuego suggests that alternative sources to the Caterina are contributing to this colonization.

In their native range, salmon are top predators in the ocean. Accordingly, exotic Chinook salmon in New Zealand (James and Unwin 1996) and in Argentina (Ciancio et al., 2008) prey on native fish and squid. Potential prey for Chinook salmon in the Beagle Channel are several fish species, like the Notothenioids (*Eleginops maclovinus*, *Patagonotothen tessellata*, *P. cornucola*, *P. sima*, *Paranotothenia magellanica*, *Harpagifer bispinis*), the Zoarcidae *Austrolychus depressiceps*, the galaxiid *Galaxias maculatus*, that inhabit the Ovando and Lapataia rivers, the Atherinidae *Odonthestes smitti* and *O. nigricans*, and the fuegian spratt *Sprattus fuegensis*, that migrate into the Beagle Channel every summer. Other potential prey are of king crab larvae (*Lithodes antarcticus* and *Paralomis granulosa*), the most important fishery resource in the Fuegian Channels. Exotic salmonids are also potential competitors of several marine top predators, such as the Magellan penguin and marine mammals. On the other hand, sea lions feed on Chinook salmon in these rivers (Fernández, personal observation).

The expansion of the known distribution of the species into the Beagle Channel proves the susceptibility of rivers in southern Tierra del Fuego to this species. Only on the Argentinean section of the Beagle Channel, there are at least another seven medium size rivers that could potentially be colonized by Chinook salmon (Fig. 1) and several rivers in western Tierra del Fuego, Chile. Moreover, the Beagle Channel provides a natural waterway for fish to invade Atlantic rivers of Tierra del Fuego, for marine circulation around the island has a predominantly easterly and northerly component into the Southern Patagonian Shelf (Fig. 3).

Chinook is only one of salmon species expected to expand in the region. In fact, Chinook is not being currently exploited in ocean-ranching or net pen aquaculture in Chile, being of little importance from a production point of view. The contemporary expansion of the species is largely driven by dispersion from an established, feral population. Meanwhile, Chile has become a leading net pen salmon producer in the World, based primarily on Atlantic and Coho salmon. Moreover, we had already

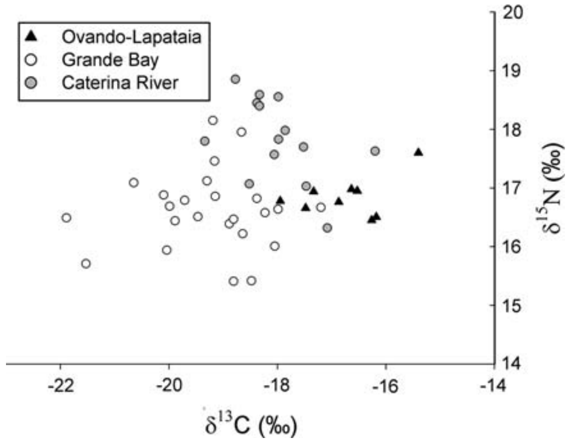

Fig. 3 Stable isotope values for the fish from Ovando-Lapataia and Caterina populations (including the ocean-bound population, Grande Bay)

captured a Coho salmon in the Lapataia River in 2007. As aquaculture moves south from the most traditional production grounds in northern Pacific Patagonia, we need to anticipate its potential effects on both marine and freshwater ecosystems. Our results indicate that, in practice, no district of Patagonia is sheltered from the colonization by exotic anadromous salmonids.

Acknowledgments This work was supported by a specific grant from Argentinean Association of National Parks (APN), and grants from National Council of Scientific and Technological Research (CONICET), Federal Council of Science and Technology (COFECyT) and the National Agency for the Promotion of Science and Technology (FONCyT). We would like to thank Dr. F. Botto and Dr. O. Iribarne for SIA analysis, Park Rangers of the National Park Tierra del Fuego for providing pictures and samples of the specimens and helping with the surveys, Facundo Llompart and Mariela Victorio for helping with the sampling, Carlos Luizón for assistance in the early identification of the species, Rodolfo Iturraspe for providing data and a map of the different river basins and Sheryl Macnie for improving the English of the manuscript.

References

Becker LA, Pascual MA, Basso NG (2007) Colonization of the Southern Patagonia Ocean by exotic chinook Salmon. Conserv Biol 21:1347–1352

Ciancio JE, Pascual MA, Lancelotti J, Riva Rossi C, Botto F (2005) Natural colonization and establishment of a chinook salmon, *Oncorhynchus tshawytscha*, population in the Santa Cruz River, an Atlantic basin of Patagonia. Environ Biol Fish 74:219–227

Ciancio JE, Pascual MA, Botto F, Amaya-Santi M, O'Neal S, Riva Rossi C, Iribarne O (2008) Stable isotope profiles of partially migratory salmonid populations in Atlantic rivers of Patagonia. J Fish Biol 72:1708–1719

Correa C, Gross MR (2008) Chinook salmon invade southern South America. Biol Invasions 10:615–639

Di Prinzio CY, Pascual MA (2008) The establishment of exotic Chinook salmon (*Oncorhynchus tshawytscha*) in Pacific rivers of Chubut, Patagonia, Argentina. Ann Limnol 1: 61–68

Doucett RR, Booth RK, Power G, McKinley RS (1999) Effects of the spawning migration on the nutritional status of anadromous Atlantic salmon (*Salmo salar*): insights from stable-isotope analysis. Can J Fish Aquat Sci 56: 2172–2180

Healey MC (1991) Life history of chinook salmon (*Oncorhynchus tshawytscha*). Pacific salmon life histories, pp 311–394

James GD, Unwin MJ (1996) Diet of chinook salmon (*Oncorhynchus tshawytscha*) in Canterbury coastal waters, New Zealand. N Z J Mar Fresh Res 30:69–78

Koo TS, Isarankura A (1967) Objective studies of scales of Columbia River chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). Fish Bull 66:165–180

Mezga B (2009) Genética de la Invasión del Salmón Chinook (*Oncorhyncus tshawytscha*) en Patagonia Argentina-Chilena. Dissertation, National University of Patagonia San Juan Bosco

Michener RH, Schell DM (1994) Stable isotope ratios as tracers in marine aquatic food webs. In: Lajtha Michener (ed) Stable isotopes in ecology and environmental science. Blackwell, London, pp 138–157

Nielsen JL (1998) Population genetics and the conservation and management of Atlantic salmon (*Salmo salar*). Can J Fish Aquat Sci 55:145–152

Pascual MA, Ciancio JE (2007) Introduced anadromous salmonids in Patagonia: risk, uses, and a conservation paradox. In: Bert T (ed) Ecological and genetic implications of aquaculture activities. Kluwer, Norwell

Pascual MA, Bentzen P, Riva Rossi C, Mackey G, Kinnison M, Walker R (2001) First documented case of anadromy in a population of introduced rainbow trout in Patagonia, Argentina. Trans Am Fish Soc 130:53–67

Pascual MA, Macchi P, Urbanski J, Marcos F, Riva Rossi C, Novara M, Dell'Arciprete P (2002) Evaluating potential effects of exotic freshwater fish from incomplete species presence–absence data. Biol Invasions 101:113

Quinn TP, Nielsen JL, Gan C, Unwin MJ, Wilmot R, Guthrie C, Utter FM (1996) Origin and genetic structure of chinook salmon, *Oncorhynchus tshawytscha*, transplanted from California to New Zealand: allozyme and mtDNA evidence. Fish Bull 94:506–521

Quinn TP, Kinnison MT, Unwin MJ (2001) Evolution of chinook salmon (*Oncorhynchus tshawytscha*) populations in New Zealand: pattern, rate, and process. Genetica 112:493–513

Sambrook J, Russell DW (2001) Molecular cloning: a laboratory manual. Cold Spring Harbor Laboratory Press, New York

Soto D, Arismendi I, Prinzio CDI and Jara F (2007) Establecimiento del salmón Chinook (*Oncorhynchus *tshawytscha*) en cuencas del Pacífico sur de Sudamérica y sus potenciales implicancias ecosistémicas. Rev Chil Hist Nat 81–98

Unwin MJ, Lucas DH (1993) Scales characteristics of wild and hatchery chinook salmon (*Oncorhynchus tshawytscha*) in the Rakaia River, New Zealand, and their use in stock identification. Can J Fish Aquat Sci 50:2475–2484

Van der Zanden MJ, Rasmussen JB (2001) Variation in δ ^{15}N and δ ^{13}C trophic fractionation: implications for aquatic food web studies. Limnol Oceanogr 46:2061–2066