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Are salmon-derived nutrients being incorporated in food webs of invaded streams? Evidence from southern Chile

I. Arismendi[(1)*], and D. Soto[(2)]

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ABSTRACT

Key-words:
invasive species, Patagonia, salmonids, periphyton, freshwater snail

Using stable isotope analyses of N and C we present preliminary evidence of marine-derived nutrients from introduced Chinook salmon (*Oncorhynchus tshawytscha* Walbaum) in stream food webs of Laguna Los Patos, NW Patagonia. Similar to values reported within Chinook salmon's native distributional range periphyton and aquatic insects are the trophic levels that show the greatest enrichment of $\delta^{15}N$ (5–6‰). Since there is a rapid expansion of Chinook salmon in South America future effort is needed to elucidate the mechanisms and consequences of nutrients subsidies from salmon carcasses in those invaded ecosystems.

RÉSUMÉ

Les nutriments dérivés du saumon sont-ils incorporés dans les réseaux trophiques des cours d'eau envahis ? Un cas au sud du Chili.

Mots-clés :
espèces envahissantes, Patagonie, salmonidés, périphyton, mollusques d'eau douce

En utilisant l'analyse des isotopes stables de N et C, nous présentons des données préliminaires indiquant que les éléments nutritifs provenant du saumon Chinook introduit (*Oncorhynchus tshawytscha* Walbaum) entrent dans le réseau trophique de la rivière Laguna Los Patos, NW Patagonie. Comme pour les valeurs rapportées dans l'aire de répartition d'origine du saumon Chinook, le périphyton et les insectes aquatiques sont les niveaux trophiques qui montrent le plus grand enrichissement de $\delta^{15}N$ (5–6 ‰). Comme il s'agit d'une expansion rapide du saumon Chinook en Amérique du Sud, un effort de recherche est nécessaire pour comprendre les mécanismes et les conséquences des apports en substances nutritives provenant des carcasses de saumons dans ces écosystèmes envahis.

Marine derived nutrients (MDN) from Chinook salmon carcasses play an important role by providing nutrients to freshwater ecosystems in the Northern Hemisphere (Wold *et al.*, 1999; Wipfli *et al.*, 2003; Claeson *et al.*, 2006; Verspoor *et al.*, 2011). The impact of MDN on stream food webs is often manifested through increased production of periphyton and biofilm (Wold *et al.*, 1999; Kohler *et al.*, 2008) and the subsequent productivity of higher trophic levels (Claeson *et al.*, 2006; Kohler *et al.*, 2008). MDN from salmon carcasses have been shown to

(1) College of Ocean, Earth, and Atmospheric Sciences, Oregon State University, 104 CEOAS Admin Bldg, Corvallis, 97331 Oregon, USA
(2) Inland Water Resources and Aquaculture Service (FIRI), Fisheries Department, FAO of United Nations, Via delle Terme di Caracalla, 00100, Rome, Italy
** Corresponding author: Ivan.Arismendi@oregonstate.edu.*

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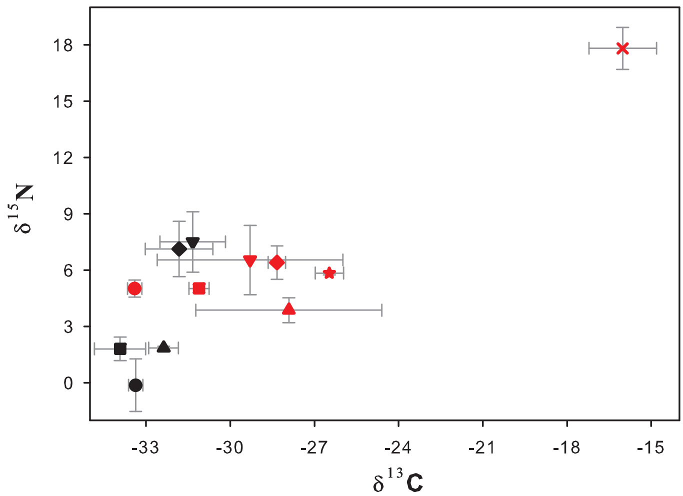

Figure 1
Dual stable isotopes plot of food webs in the stream influenced by MDN from salmon carcasses Laguna Los Patos (red symbols) and in the reference stream Rio Pescado (filled symbols). Symbols (mean ± SE) represent peryphyton (circle), freshwater snail (triangle), aquatic insects (square), brown trout (diamond), rainbow trout (inverted triangle), Chinook salmon fry (star), and Chinook salmon carcasses (× symbol).

increase the growth rate of resident salmonids in streams and improve the freshwater and marine salmon production (Wipfli *et al.*, 2003).

In recent decades, rapid colonization and establishment of self-sustaining populations of Chinook salmon (*Oncorhynchus tshawytscha* Walbaum) have occurred in South America (Becker *et al.*, 2007; Soto *et al.*, 2007; Correa and Gross, 2008; Di Prinzio and Pascual, 2008) and New Zealand (McDowall, 1994). Although MDN from salmon carcasses provide multiple benefits in ecosystems where Chinook salmon is native, whether or not similar benefits will occur in systems in which they are introduced remains unclear. Additionally, it is also not known whether the nutrients from introduced salmon carcasses become incorporated into the aquatic food webs in the same way.

Several studies conducted in North America have used stable isotopes of carbon (C) and nitrogen (N) to address the importance of MDN from salmon carcasses transported into freshwaters (*e.g.* Wold *et al.*, 1999; Chaloner *et al.*, 2002; Claeson *et al.*, 2006; Kohler *et al.*, 2008). During their ocean life history, adult Chinook salmon incorporate heavier isotopes of C and N from marine sources and because they do not feed when they enter to the freshwater this signature is retained and different than a terrestrial or freshwater origin. Thus, food webs that incorporate MDN from salmon carcasses should show predictable changes from their previous natural isotopic signatures. Here, by using stable isotopes of C and N we examine if MDN from salmon carcasses are being incorporated in food webs of an invaded stream where Chinook salmon have become established in recent decades. Our results provide the first attempt to evaluate the importance of MDN from salmon carcasses in Patagonia which is essential information to testing impacts of Chinook salmon invasions in southern South America and elsewhere.

We sampled in two adjacent Andean streams within 20 km, Laguna Los Patos (invaded by Chinook salmon) and Rio Pescado (not-invaded), both located in the Chilean Lakes Region in southern South America (39° 30'–43° 35' S). We selected these two streams based on their high similarity of key characteristics that influence the stream productivity and thus, we minimize potential confounding factors that could obscure our results of MDN in their food webs (*e.g.*, light, discharge, substrate, geology, biota; Figure 1 and Table I). Both sites originate on volcanic slopes of 2000–2700 m elevation and drain relatively pristine watersheds with riparian vegetation dominated by the Valdivian temperate rainforest. As part of the Vicente Perez Rosales National Park, Laguna Los Patos is the first and most studied

Table I
Characteristics of the two selected streams (Laguna Los Patos and Rio Pescado) sampled in April-May of 2007–2008. Mean values were obtained during the sampling period.

	Laguna Los Patos river with Chinook	Rio Pescado reference river without Chinook
***UTM coordinate East**	713 332	68 571
***UTM coordinate North**	5 438 389	5 429 128
Watershed area (ha)	7 869	7 729
Main watershed name	Petrohue	Maullin
Mean stream flow ($m^3 \cdot s^{-1}$)	5.4	4.9
Mean velocity ($m \cdot s^{-1}$)	0.85	0.69
Mean with (m)	17.5	21.2
Mean depth (m)	0.76	0.6
Mean temperature (ºC)	10.15	10.18
Mean conductivity ($\mu S \cdot cm^{-1}$)	87	38.5
Mean pH	8.1	8.2
Mean dissolved O_2 ($mg \cdot L^{-1}$)	7.2	7.8
Mean % of boulders	62	68

* UTM = Universal Transverse Mercator Geographic Coordinate System.

spawning site of Chinook salmon in Chile (Soto *et al.*, 2007). In Laguna Los Patos, non-native rainbow trout (*O. mykiss* Walbaum) and brown trout (*Salmo trutta* L.) are the most common fishes and Chinook salmon parr can be found seasonally from spring to early summer (September–January; Soto *et al.*, 2007). Native fishes, including *puye chico* (*Galaxias maculatus* Jenyns) and *puye grande* (*G. platei* Steindachner) are also present but in much lower densities. At the Rio Pescado reference site, the fish assemblage is similar to Laguna Los Patos except that Chinook salmon has never been reported there (Soto *et al.*, 2007; Correa and Gross, 2008).

We visited both sites during April and May (2007–2008) to cover the end of the Chinook salmon breeding season (Soto *et al.*, 2007). In Laguna Los Patos, we sampled 50–200 m downstream of the Chinook salmon historical spawning area and in the reference site we randomly selected a comparable reach with similar hydrological and riparian vegetation characteristics (Table I). We examined the potential use of MDN from salmon carcasses in freshwater food webs using stable isotopes of C and N in periphyton, macroinvertebrates (scrapers), and fishes. We sampled periphyton by scraping the dominant cobble substrate. We collected macroinvertebrates *(i.e.* aquatic insects and freshwater snail *Chilina* sp.) by using a 25 cm diameter stovepipe benthic sample corer. We sampled fishes by using standard electrofishing procedures obtaining a dorsal portion of muscle from rainbow trout and brown trout (15 to 25 cm total length), Chinook salmon carcasses (90 to 120 cm total length), and Chinook salmon parr (5 to 10 cm total length). We stored tissues at 0 °C for transportation. In the laboratory they were dried at 60 °C for 48 h and ground into a fine powder. We analyzed all samples at the Stable Isotope Research Unit, Crop and Soil Sciences Department, Oregon State University. Isotope ratios were expressed in parts per thousand (‰) according to the equation:

$$X = [(R_{sample} - R_{standard}) / R_{standard}] \times 10^3$$

Table II
Stable isotopes of N and C from different studies in southern South America conducted in streams invaded by Chinook salmon and in reference systems. SD = standard deviation; Ref = Reference; Chi = Chinook salmon invaded. For the nutrient origin T = terrestrial, F = freshwater, and M = marine.

Item	Category	Ref/Chi	Origin	Range/mean $\delta^{15}N$	SD	Range/ mean $\delta^{13}C$	SD	n	Study area	Citation
Soil	Andes mountains	Ref	T	–2.90		–28.30			Southern Chile	(4)
	Old–growth forest	Ref	T	–4.00					Southern Chile	(2)
Primary production	Periphyton	Ref	F	–0.14	1.40	–33.37	0.26	4	Pescado River, Chile	Present study
		Chi	F	5.00	0.46	–33.40	0.26	3	Laguna Los Patos, Chile	Present study
Secondary production	Aquatic insects	Ref	F	1.80	0.63	–33.92	0.91	2	Pescado River, Chile	Present study
		Chi	F	5.01	0.22	–31.11	0.36	3	Laguna Los Patos, Chile	Present study
	Freshwater snail	Ref	F	1.85	0.66	–32.37	0.52	2	Pescado River, Chile	Present study
		Chi	F	3.86	0.08	–27.91	3.31	5	Laguna Los Patos, Chile	Present study
Brown trout	Free–living	Ref	F	7.12	1.47	–31.82	1.20	10	Pescado River, Chile	Present study
		Chi	F	6.40	0.89	–28.34	0.31	8	Laguna Los Patos, Chile	Present study
		Ref	F	5.00 to 11.60					Southern Chile	(1)
Rainbow trout	Free–living	Ref	F	7.50	1.61	–31.33	1.17	8	Pescado River, Chile	Present study
		Chi	F	6.54	1.85	–29.29	3.30	8	Laguna Los Patos, Chile	Present study
		Ref	F	5.50 to 8.80					Southern Chile	(1)
		Ref	F	10.54		–32.65			Southern Chile	(7)
	Farmed	Ref	F/M	15.10		–27.74			Southern Chile	(7)
	Anadromous	Chi	F	14.41 to 16.08		–20.21 to –18.12			Santa Cruz River, Argentina	(3)
Chinook salmon	Introduced/ fry	Chi	F	5.83	0.09	–16.02	1.21	10	Laguna Los Patos, Chile	Present study
	Adult–carcasses	Chi	M	17.81	1.12	–26.47	0.50	5	Laguna Los Patos, Chile	Present study
		Chi	M	17.07 to 18.85		–19.30 to –17.44			Caterina, Argentina	(3)
		Chi	M	16.8 to 18.15		–19.19 to –17.23			Grande Bay, Argentina	(3)
		Chi	M	16.20 to 17.80		–18.00 to –15.50			Ovando–Capataia, Argentina	(5)
Marine fishes	Anchovy	Ref	M	17.83		–15.56			Chile	(6)
	Hake	Ref	M	17.67		–14.42			Chile	(6)
	Herring	Ref	M	17.67		–14.61			Chile	(6)
Marine mammals	Sea Lion	Ref	M	20.97		–12.48			Chile	(6)

(1) Arismendi *et al.*, 2011; (2) Boeckx *et al.*, 2005; (3) Ciancio *et al.*, 2005; (4) Etcheverría *et al.*, 2009; (5) Fernández *et al.*, 2010; (6) Hückstädt *et al.*, 2007; (7) Schröder *et al.*, 2010.

where *X* is $\delta^{13}C$ or $\delta^{15}N$ and *R* is the corresponding ^{13}C:^{12}C or ^{15}N:^{14}N ratio. The standards used were Vienna Peedee belemnite for C and N_2 for N. Positive delta values indicated enrichment of the heavier isotope and negative values indicated depletion.

Because of the difficultly in locating additional streams with a long-term history of confirmed Chinook salmon spawning within 500 km of Laguna Los Patos (see Correa and Gross, 2008) we contrasted our results with other studies in streams of Patagonia with and without the presence of Chinook salmon (Table II).

At the reference site, periphyton was highly depleted in $\delta^{15}N$ compared to Laguna Los Patos and had a comparable level to the terrestrial soils (Figure 1, Table II). Also, at the reference site, aquatic insects (scrapers) and freshwater snails were more depleted in $\delta^{15}N$ compared to fishes. Conversely, there were a similar enrichment in $\delta^{15}N$ on periphyton, aquatic insects, freshwater snails and fishes at Laguna Los Patos. Moreover, Chinook salmon was highly enriched of $\delta^{13}C$ followed by Chinook parr at Laguna Los Patos but, periphyton showed a similar and depleted level of $\delta^{13}C$ at both sites. Aquatic insects, freshwater snail, and fishes were more enriched of $\delta^{13}C$ at Laguna Los Patos than at the reference site. Rainbow trout and freshwater snails had the greatest variability in $\delta^{13}C$, a different pattern than seen at the reference site.

Our results suggest that MDN from salmon carcasses are most likely being incorporated into stream food webs of an invaded river where Chinook salmon is well established. Specifically, at Laguna Los Patos, periphyton and aquatic insects show the greatest enrichment of $\delta^{15}N$ (5–6‰), similar to enrichment levels reported in Alaska (Chaloner *et al.*, 2002). Our results are also in agreement with the idea that periphyton and aquatic insects are two lower trophic levels that better incorporate the MDN from salmon carcasses as seen in North America (Wold *et al.*, 1999; Chaloner *et al.*, 2002; Claeson *et al.*, 2006; Kohler *et al.*, 2008).

The role of salmon carcass inputs in South American streams is ecologically interesting because it illuminates the function of nutrient subsidies from an invasive species perspective. This may be important in resource-limited systems such as southern Chilean streams (Campos, 1985) where MDN subsides from Chinook salmon carcasses could also facilitate other invasions (*i.e.*, rainbow and brown trout; see Kiernan *et al.*, 2010). In North American streams MDN from salmon carcasses have been linked to increases in growth rates, survival and reproduction of native salmonids (Chaloner *et al.*, 2002; Wipfli *et al.*, 2003; Kiernan *et al.*, 2010), but the expected impacts may vary depending on local availability of nutrients or other food web processes (Stockner, 2003). The higher variability of $\delta^{13}C$ observed in rainbow trout and freshwater snails could be result of direct consumption of salmon material (*i.e.* we observed *in situ* salmon eggs in trout stomachs and freshwater snails grazing over salmon carcasses).

In their native ecosystems salmon carcasses affect both heterotrophic and autotrophic processes (Holtgrieve and Schindler, 2011) with ecological consequences that persist over time (Verspoor *et al.*, 2011). However, in invaded systems we still understand little about how these newly available nutrient subsidies may change ecosystem functioning. Since Chinook salmon are currently undergoing rapid expansion in South America (Correa and Gross, 2008) further efforts are needed to elucidate the consequences of MDN at a broader scale. This is a preliminary study that provides a first attempt to identify where MDN from Chinook salmon carcasses are being incorporated in food webs of invaded streams but it lacks replication. We encourage future studies to include more sites covering a broader extent range of stream types invaded and not invaded by Chinook salmon. Further, studies that consider riparian zones in streams where Chinook salmon have been introduced, including plants (*i.e.* N-fixing species) and terrestrial organisms, will illuminate our understanding about if MDN are also being transported and incorporated in those terrestrial ecosystems.

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