Behavioral and Biochemical Adaptations of Juvenile Pacific Salmon in the Okhotsk Sea and Northwestern Pacific Ocean

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Within their phenotype, salmon are a very flexible group of fish with highly variable life histories (Pavlov 1994; Pavlov et al. 2010). Throughout life they periodically move between ecosystems, and in response to these changes there is an adaptation to different abiotic and biotic environments. A distinctive feature of the habitat adaptation period that is different from the other stages of ontogeny is the transition of the energy budget from surplus to deficit, expressed in the intensive use of food reserves, mainly triacylglycerols (Sidorov 1983). Our objective was to identify fluctuations of total lipid and protein content in juvenile salmon and to relate these variations to critical stages in the life of Pacific salmon.

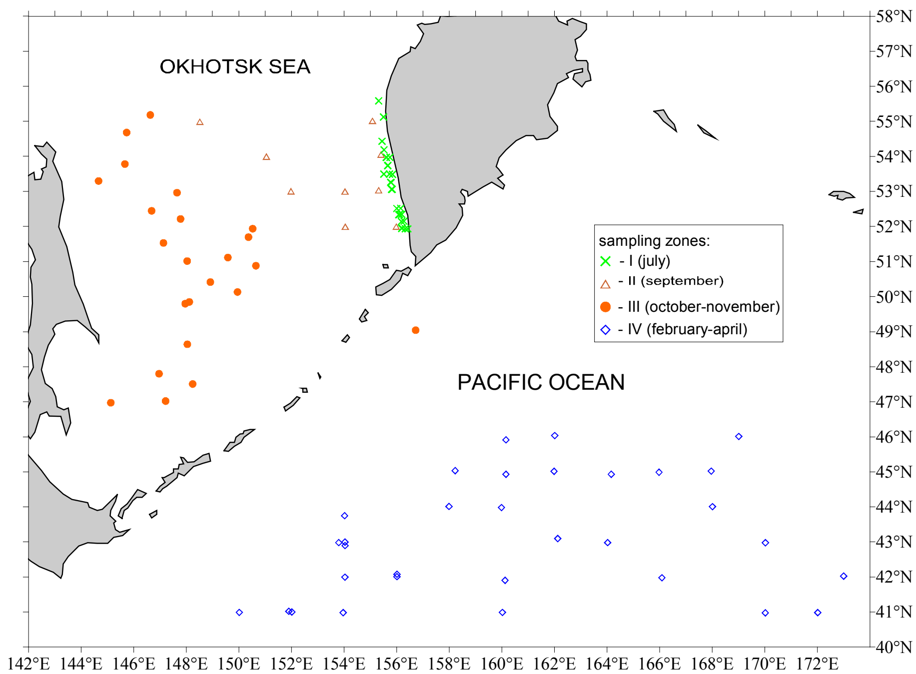

Fig. 1. Location of survey stations and sampling zones in the Okhotsk Sea and northwestern Pacific Ocean where chum, pink, and sockeye salmon tissue samples were collected for biochemical analysis of lipid and protein content.

Samples for biochemical analysis were collected during trawl operations conducted in four geographic zones that included coastal and offshore waters of western Kamchatka, Okhotsk Sea, and northwestern Pacific Ocean (Table 1; Fig. 1). From each trawl operation, 50-100 salmon were examined for full biological analysis that included measurement of body size and weight, gonad weight, determination of sex, and collection of scales and otoliths. For biochemical analysis, 5-30 fish were collected at selected trawl sites. A piece of muscle tissue was collected from near the dorsal fin, along the body from the top of the back to the lateral line. Muscle tissue was excised together with subcutaneous fat. Individual sample weights ranged from 15 to 20 g. Muscle tissue collected during the expeditions was stored at -20ºC. In the laboratory, samples were homogenized in a solution of chloroform-ethanol (2:1) and stored at -20ºC until analysis was completed. The lipids were extracted by chloroform-ethanol (2:1; Folch et al. 1957). The total lipid content was determined by the gravimetric method (Kates 1975). Weight of non-fat solids (IDS) was collected to determine the protein content of muscle tissue, which is known to consist of more than 90% protein in fish (Shulman and Love 1999). In total, 209 pink, 192 chum, and 110 sockeye salmon were analyzed for lipid and protein content.

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Table 1. Sampling areas of the Okhotsk Sea and northwestern Pacific Ocean and months when chum, pink, and sockeye salmon tissue samples were collected for biochemical analysis.

Zone	Time	Place
I	July 2010, 2011	Coastal waters of the western Kamchatka
II	September 2011	Coastal waters of the western Kamchatka and free waters of the Sea of Okhotsk
III	October–November 2010, 2011	Northern and southern part of the free waters of the Sea of Okhotsk, Kuril Pacific Ocean
IV	February–April 2010, 2011	Pacific Ocean in the area of the subarctic front

Results from the July 2010 and 2011 samples showed there was a trawl take of juveniles in the coastal waters of western Kamchatka. Analysis of muscle tissue in all species showed low lipid content of not more than 1.6% on average (Fig. 2). Such lipid levels are observed annually at all stations located in zone I (Fig. 1; Tables 2-4). This period in the development of Pacific salmon continues all summer, and we have identified this as an adaptation period to the sea. During the period of adaptation to marine habitats, juveniles remain mainly in coastal waters (Shuntov and Temnykh 2008).

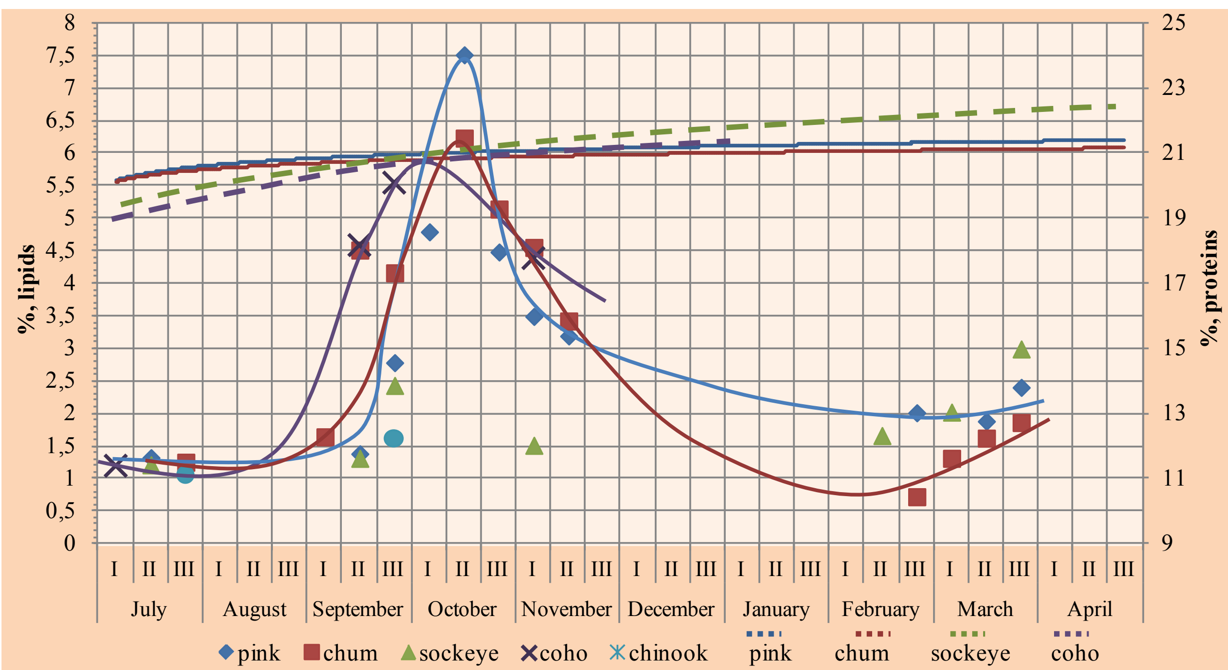

Fig. 2. Seasonal dynamics of total lipid (left y-axis) and protein content (right y-axis) of muscle tissue collected from juvenile salmon during postcatadromous migrations in the Okhotsk Sea.

After completion of the adjustment period of pink and chum salmon, amid the mass migration to the open waters of the Sea of Okhotsk, there is a transition of the energy budget from deficit to surplus. This is accompanied by an increase in the growth rate recorded by accumulation of proteins and active deposition of fat (Tables 2 and 3). Sockeye salmon completing the adaptation period migrate northwards along the coast of western Kamchatka (Erokhin and Shershneva 2007). In sockeye salmon we have not observed rapid changes in the accumulation of nutrients at this time. Such change in behavior in Pacific salmon occurs in early autumn (Table 4).

Table 2. Juvenile pink salmon size and protein (% wet weight) and lipid content (% wet weight) determined from fish caught in the Sea of Okhotsk in 2010 and 2011. Numerator is the average value, denominator is the range.

Years	2011						2010		2011	
Period	July	September			October		November		February–April	
Body length	7.4	16.4	19.9	23.9	22	23.6	24	26	29	35
AC, cm	6,5–8	14.5–17.5	18–22	23–25	20–22	23–25	21–25	25–28	24.4–32	32.6–40.2
Weight, g	7	40	80	133	103	136	128	187	244	428
	6–8	25–58	49–120	105–156	65–122	102–192	85–148	152–252	140–335	332–684
Protein, %	22.28	20.21	19.84	20.24	19.62	19.83	21.45	21.91	19.85	20.49
wet weight		19.09–23.42	18,3–22,38	19,79–21,05	16.92–22.3	16.73–21.73	20.77–22.2	20.49–22.82	15.17–26.94	17.44–24.59
Lipids, %	1.33	1.8	1.88	2.12	4.8	5.16	3.48	3.99	1.84	2.61
wet weight		1.18–2.43	1,2–2,97	1,46–2,49	2.09–8.92	2.63–9.6	1.52–5.74	2.49–5.89	1.34–2.19	1.55–4.18

Table 3. Juvenile chum salmon size and protein (% wet weight) and lipid content (% wet weight) determined from fish caught in the Sea of Okhotsk in 2010 and 2011. Numerator is the average value, denominator is the range.

Years	2010	2011							2010	2011
Period	July	July	September				October		November	February–April
Body length	7	8	16	19	22.5	27	22.4	26	22	25
AC, cm	6–8.7	5–11	13–17.5	18.0–20	20.5–24.5	25–30	20–25	25–27	21–23	22.8–28.7
Weight, g	3	6	44.7	77.3	129.6	222.1	121	196	124	158
	2–6	2–14	28–62	58–109	88–188	186–340	84–178	162–232	102–215	112–217
protein, %	20.22	19.97	19.97	20.97	21.50	22.01	20.16	20.48	22.36	21.28
wet weight	18.80–22.13	19.3–20.65	17.09–21.53	19.14–22.97	19.37–23.12	20.81–23.87	17.45–22.53	19.13–21.23	21.79–23.29	18.84–25.08
lipids, %	1.56	1.26	1.38	1.93	3.15	5.01	4.02	5.52	4.01	1.71
wet weight	0.96–2.25	1.04–1.59	1.04–1.88	1.2–3.52	1.37–5.91	2.74–7.97	1.54–7.34	3.31–8.5	2.22–6.09	0.95–3.12

In October, juvenile pink and chum salmon caught in the Okhotsk Sea were characterized by the highest deposition of fat (Fig. 2). High physical activity compensated for by excessive food supply and optimal temperatures for juveniles in the northern Sea of Okhotsk together supply a surplus energy budget, which in turn is reflected in the deposition of nutrients in the tissues, including fat in the muscle (Sidorov 1983; Shulman and Love 1999; Erokhin and Klimov 2010; Tables 2 and 3). Sockeye salmon sized 36-42.5 cm and caught in October near the southern tip of the Kamchatka Peninsula and the northern Kuril Islands on the Pacific side also exhibited high lipid levels (Fig. 1). The lipid status of these sockeye salmon ranged from 1.06–3.20% and averaged 1.81% (Table 4). Judging by the body size, these sockeye salmon were in their second ocean year.

Table 4. Juvenile sockeye salmon size and protein (% wet weight) and lipid content (% wet weight) determined from fish caught in the Sea of Okhotsk in 2010 and 2011. Numerator is the average value, denominator is the range.

Years	2010		2011				2010		2011		
Period	July		July		September		November		February–April		
Body length	10	16	10	14	18.5	21.2	25	37	28	38	48
AC, cm	6.7–13.9	14.6–18.2	7.9–12.5	13–15.7	17–19.5	20–23.5	24–26	33–42	21.5–30.4	35.3–40	41.5–53.4
Weight, g	13	43	12	32	74	111	166	571	226	634	1270
	3–34	32–66	5–22	23–44	50–87	87–145	146–192	384–848	92–308	498–787	793–1751
protein, %	20.30	20.30	20.40	20.41	19.98	20.29	23.08	23.15	23.94	21.55	21.51
wet weight	19.02–21.30	18.18–23.12	18.62–22.04	19.08–21.87	19.26–22.10	19.59–21.41	22.54–23.53	22.19–24.44	22.25–25.62	20.77–22.46	20.43–22.14
lipids, %	1.17	1.53	1.18	1.22	1.43	1.77	1.52	1.81	1.67	2.5	2.99
wet weight	0.49–1.81	0.48–2.12	0.64–1.79	0.78–1.66	1.01–2.75	1.04–2.85	1.12–1.84	1.06–3.20	0.62–2.08	1.1–4.57	1.43–4.76

In November during the migration of pink and chum salmon to the southern Okhotsk Sea, the proportion of lipids in muscle tissue declined. The same was true for sockeye salmon. In the southwestern part of the Okhotsk Sea, juvenile sockeye salmon collected in November had lower lipid levels than in the previous month as levels ranged from 1.12 to 1.84% and averaged 1.52%.

From November to December, juvenile Pacific salmon migrate to the northwestern Pacific Ocean (Shuntov and Temnykh 2008). Passing through the Kuril straits, young pink and chum salmon begin adapting to the ocean. Over the three to four months in the ocean, young fish lose up to 80% of the lipids they accumulated during autumn feeding (Tables 2 and 3). The total lipid content in juvenile sockeye salmon did not decrease, but increased on average up to 9% (1.67%) in comparison with young fish caught in November (1.52%). We suggest that fish size groups of 35–40 cm (498–787 g) and 41.5–53 cm (793–1751 g) as the sizes of salmon that start feeding again in the ocean in the spring (Table 4).

The protein component of muscle tissue was static in comparison with total lipids levels. In the developmental interval between fertilization and when the fish they reach the ocean, the protein level in the muscle tissue undergoes two major changes. First, when the energy needs during embryonic development has expended up to 40% of the protein, then protein levels are restored by in-river feeding (Sidorov 1983). The second change concerns with adaptation by young fish to sea life (Fig. 2). As metabolism of lipids and carbohydrates of juveniles in the sea is dominated by catabolic processes, protein metabolism is predominately an anabolic process, requiring energy for biosynthetic transformations (Varnavskiy 1991).

To review, the first year of life of juvenile salmon in the sea has been divided into three stages: (1) early life and adaptation in the sea (June-August), (2) intensive autumn feeding (September-October), and (3) movement and adaptation to the open ocean (November ~April). The process of migration for juvenile salmon causes a significant expenditure of energy, with a corresponding reduction of the primary energy source—lipids—from the fish's body by a level of three times or more. Adaptation to new habitat conditions by juveniles is also accompanied by increased utilization of ingested energy during the early stages of coastal foraging. At the same time, much of the energy is used for protein synthesis to quickly out-grow the prey size range of various predators, which are a new significant threat in such an environment. In connection with this, we did not observe a decline in the content of proteins during the transition to sea life or during the sea stage.

According to the available data set, the duration of the adaptation of juvenile salmon to the marine period includes all summer months. Apparently, the time boundary when fish start to actively replenish their fat reserves and energy potential is August. Following this time, there is a strong increase in total calories and lipid content in pink and chum, but not sockeye salmon. When foraging at the coast, juvenile sockeye salmon exhibit few changes in muscle lipid content and levels remain low in comparison with chum and pink salmon. The reduced lipid level (to 80%) of juvenile chum and pink salmon indicates the migration out to sea plays an important role in ontogeny, comparable with the early marine adaptation period. However, this is not true for sockeye salmon because the lipid content does not fall as lipid levels increase on average 9%.

Based on analysis of the information presented here, we conclude there are two different strategies for developing offshore feeding areas and biochemical adaptation. On the one hand, juvenile pink and chum salmon, which migrate over vast sea areas, actively put on weight and then spend most of the accumulated nutrients during their migration to the ocean. On the other hand, juvenile sockeye salmon put on weight only in coastal waters and maintain a low lipid level from the time of their initial migration to marine waters through to their movement to the open ocean.

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