Differential Seawater Adaptability in Three Different Sizes of Under-yearling Steelhead Trout

Myeongseok Lee¹ and †Jang-Won Lee¹²

¹Dept. of Integrated Bio-Industry, Sejong University, Seoul 05006, Korea
²Sejong Institute of Salmonid Research, Sejong University, Seoul 05006, Korea

Abstract

Seawater adaptability of steelhead trout increases along with the increase in the size of the fish, independent of parr-smolt transformation. Three 96 h seawater challenge tests were conducted to determine the size at which seawater adaptability of steelhead trout develops. Plasma Na⁺ and Cl⁻ levels, moisture content, gill Na⁺/K⁺ ATPase activity, and mortality during the 96 h after direct transfer to seawater (32 ppt) were determined. Plasma Na⁺ and Cl⁻ levels in 50 g fish continuously increased during the 96 h after the transfer to seawater (p<0.05), but the levels in 100 and 150 g fish leveled off after 24 h (p<0.05). Both 100 and 150 g size steelhead trout maintained muscle moisture content (%) better than 50 g size fish (p<0.05). Gill Na⁺/K⁺ ATPase activity in the 100 g size group increased in a time-dependent manner after transfer to seawater (p<0.05), whereas activity in the 50 and 150 g sizes did not increase (p>0.05), for which a possible explanation was discussed. A mere 2.6% mortality in both the 50 and 150 g size groups was observed. In conclusion, the current results indicate that 50 g size steelhead trout did not show development of a high level of hypoosmoregulatory capacity, whereas fish in the 100 and 150 g size groups showed a high level in our experimental conditions. Therefore, the steelhead trout larger than a 100 g size is recommended for transfer to seawater culture.

Keywords: Steelhead trout, Seawater adaptation, Osmoregulatory capacity, Na⁺/K⁺ ATPase activity, Plasma ion levels, Muscle moisture

INTRODUCTION

There are two different strains of the Oncorhynchus mykiss species, anadromous and land-locked strains (Moyle, 2002). Steelhead trout is an anadromous strain of O. mykiss and is also called steelhead salmon (more biological perspective) due to its salmon-like life history (Quinn & Myers, 2004). In Korea, landlocked domesticated strain of O. mykiss has mainly been cultured in freshwater but recently seawater farming of the O. mykiss has been attracting more interest due to the larger harvest sizes in sea cages (Shin et al., 2011). Aquaculture of steelhead has been attempted in an effort to improve seawater acclimation of O. mykiss (Xiong et al., 2020). Although steelhead trout is generally known to be more readily adaptive to seawater than rainbow trout (Wagner, 1974; Prunet & Boeuf, 1985; Johnsson & Clarke, 1988; Xiong et al., 2019), specific information on elements affecting seawater adaptability of
Steelhead trout is crucial for the seawater transfer to be successful.

Parr-smolt transformation (also called smoltification) is a series of developmental changes juvenile anadromous salmonids undergo, during which the juvenile salmon acquires hypoosmoregulatory capacity to survive in salt water before seaward migration (McCormick & Saunders, 1987; Hoar, 1988; Boeuf, 1993; Björnsson et al., 2011). The complete parr-smolt transformation usually includes morphological (silvering), behavioral (pelagic schooling), and physiological (hormonal and enzymatic) changes (Hoar, 1976; McCormick & Saunders, 1987; Hawkings et al., 2004; Riley et al., 2014). Changes in environmental factors (photoperiod, temperature, and salinity) trigger parr-smolt transformation in nature when juvenile fish reach a threshold size (Conte & Wagner, 1965; Ewing et al., 1979; Björnsson et al., 2011; Kendall, 2015), which widely varies depending on the species (Clarke, 1982; Varnavsky et al., 1991). Some studies have reported that development of seawater adaptability in *O. mykiss* occurs before the manifestation of smolification (Conte & Wagner, 1965; Wagner, 1974). These studies suggest that parr-smolt transformation and development of seawater adaptability may be two distinct physiological processes (Conte & Wagner, 1965; Wagner, 1974). Furthermore, seawater adaption of steelhead trout is reported to be a function of size rather than chronological age (Houston, 1961; Conte & Wagner, 1965). Thus, when steelhead trout reach a threshold size, they can acclimate to seawater independent of smolification (Wagner, 1974; Morro et al., 2019; Xiong et al., 2020).

In many *O. mykiss* farms in Korea, juvenile fish produced in freshwater are geographically separated from grow-out in sea cages, similar to salmon farming in the Yellow Sea of China (Xiong et al., 2020). Thus, if fish farmers were able to transfer smaller juveniles, they would have more advantages in terms of transportation as well as stress levels in fish. Although *O. mykiss* can adapt to a wide range of environmental salinity, when *O. mykiss* are transferred from freshwater to seawater, they immediately undergo water efflux (dehydration) and sodium influx. To regain internal hydromineral balance, after drinking seawater *O. mykiss* selectively excrete excess salts (particularly Na⁺ and Cl⁻) through their gills and retain water (Kültz, 2015). Na⁺/K⁺ ATPase (NKA, sodium pump) in chloride cells of the gills play a major role in the excretion of excess Na⁺ and Cl⁻ from the body. High NKA activity is an indicator of seawater adaptability of salmonids including *O. mykiss* (Bystriansky et al., 2006; Kennedy et al., 2007). However, if *O. mykiss* are transferred from freshwater to seawater before they develop efficient osmoregulatory capacity, the fish cannot increase NKA activity to a sufficient level, which results in prolongable elevation of salts (e.g., plasma Na⁺ and Cl⁻) and dehydration (e.g., muscle moisture decrease) internally, which could lead to the interruption of normal biochemical processes and physiological homeostasis (Bystriansky et al., 2006; Kennedy et al., 2007; Kültz, 2015).

In a previous study, Gorie (1993) has reported that 0+ landlocked strain of *O. mykiss* need to reach a 150 g size to acquire a high level of hypoosmoregulatory capacity in seawater. In the current study, we hypothesized that under-yearling steelhead trout acquire a high level of seawater adaptability in a relatively smaller size compared to landlocked rainbow trout. The objective of the current study was to determine seawater adaptability of under-yearling steelhead in three different sizes trout for optimal seawater transfer. The 96 h seawater challenge test included determination of plasma Na⁺ and Cl⁻ concentration, muscle moisture content, and NKA activity as indicators of seawater adaptability (Leray et al., 1981; Clarke, 1982; Madsen & Naamansen, 1989; Morro et al., 2019).

**MATERIALS AND METHODS**

1. **Fish acquisition and maintenance**

   Fries of steelhead trout strain (Troutlodge, WA, USA) were purchased and reared in 300-liter tanks.
freshwater recirculating tanks for 5 months in a laboratory at Sejong University, Seoul (temperature: 15.29±0.06 °C; photoperiod: 12L: 12D; dissolved oxygen: 7.73±0.04 mg/L; pH: 7.86±0.02; conductivity: 992.67±27.13 μS/cm). During the rearing period, fish were fed a commercial diet (protein 45%, lipid 12%–13%, ash 14%, fiber 3%) at a daily optimal ration of total body mass, twice a day (Austreng et al., 1987). 10%–20% of the water was changed daily with dechlorinated filtered freshwater and additional aeration was provided to each tank. All experimental procedures using fish followed the guidelines approved by the Institutional Animal Care and Use Committee of Sejong University, Korea.

2. Experimental procedure and sampling

The average body weight of fish and seawater parameters are presented in Table 1. As the batch of fish grew, three separate 96 h seawater challenge tests were carried out in chronological order (June, August, and November of 2019 for 50, 100, and 150 g size groups, respectively). For each test, 39 fish of similar size were selected and randomly transferred to 3 separate recirculating rectangular glass aquaria (300 liters of seawater), which resulted in 13 fish per aquarium (triplicate). All fish were fasted from 24 h before being transferred to seawater (32 ppt, Table 1) until the end of the test (96 h after the transfer to seawater). At 0, 24, 48, and 96 h after the transfer, three fish from each aquarium (9 fish per each sampling time) were randomly caught, euthanized in a buffered tricaine methanesulfonate (MS-222, 200 mg/L), and weighed. After blood was collected from the caudal vein using syringes and heparinized tubes, plasma was separated by centrifugation at 13,000 g, 4 °C for 15 min and then stored at −80°C for plasma Na+ and Cl− analyses. Six to seven gill filaments from the second arch were surgically removed, put in cold SEI buffer (250 mM sucrose, 10 mM Na2EDTA, 50 mM imidazole, pH 7.3), and instantly frozen on dry ice and stored at −80°C. White muscle without skin was surgically removed from the muscle mass between the dorsal fin and the lateral line and stored at −80°C.

3. Determination of plasma Na+ and Cl− concentrations

Plasma Na+ and Cl− concentrations were determined using an automated blood chemistry analyzer (Dri-CHEM 7000i, Fuji, Tokyo, Japan).

4. Gill Na+/K+ ATPase activity assay

The ouabain sensitive hydrolysis of adenosine triphosphate (ATP) leads to the oxidation of nicotinamide adenine dinucleotide (NADH), by pyruvate kinase and lactate dehydrogenase (LDH),

| Table 1. Average body weight, mortality, and water parameters for 96 h seawater challenge test |
|-----------------------------|-----------------------------|-----------------------------|
| **Test group** | **50 g (n=39)** | **100 g (n=39)** | **150 g (n=39)** |
| Body weight (g) | 50.4±0.5 | 103.4±1.4 | 151.8±1.8 |
| Mortality (%) | 2.6 | 0 | 2.6 |
| System | RAS | RAS | RAS |
| Water temperature (°C) | 15.17±0.07 | 15.35±0.18 | 15.19±0.13 |
| Dissolved oxygen (mg/L) | 7.93±0.09 | 7.53±0.13 | 7.76±0.05 |
| pH | 7.74±0.04 | 8.09±0.05 | 7.75±0.06 |
| Ammonia | ND | ND | ND |
| Photoperiod (L:D) | 12:12 | 12:12 | 12:12 |

Means±SE.

Detection limit: 0.25 mg/L (Tetra NH3/NH4+ Test Kit, Blacksburg, VA, USA); ND, not detected.

RAS, recirculating aquaculture system.
which is directly measured in a microplate reader at 340 nm (McCormick et al., 1993). Levels of NKA activity were determined based on previously established protocol (McCormick et al., 1993). A frozen gill sample in SEI buffer was thawed briefly and homogenized on ice using a motorized homogenizer (Power masher II, Nippi, Tokyo, Japan) in SEID buffer (0.5 g of sodium deoxycholate in 100 mL of SEI) for 20 seconds. After centrifugation (5,000 g, 4 °C, 1 min), supernatant was used for the assay: 10 μL of homogenate to each of the four wells for every sample. The remainder of the homogenate was saved and later analyzed for protein concentration (BCA protein assay, Pierce, Thermo scientific, Rockford, IL, USA). 200 μL of assay mixture A (4 U LDH/mL, 5 U pyruvate kinase/mL, 2.8 mM phosphoenolpyruvate, 0.7 mM ATP, 0.22 mM NADH, and 50 mM imidazole, pH 7.5)+salt mixture was added to two wells and 200 μL of assay mixture B (assay mixture A+0.5 mM ouabain)+salt mixture was added to the other two wells for each sample. The microplate was put into a plate reader (25 °C, Epochi 2 microplate reader, BioTek) and the decrease of NADH was measured at 340 nm for 10 min. All assay procedures were completed within 30 min of homogenization. NKA activity was calculated by the difference in ATP hydrolysis in the presence and absence of ouabain as micromoles of ADP per mg of protein per hour. All chemical reagents were purchased from Sigma-Aldrich, St. Louis, MO, USA, unless noted otherwise.

5. Statistical analysis

All data was statistically analyzed using SPSS Statistics 24 (IBM, Chicago, IL, USA). A two-way ANOVA model was used to test the main effects of size and time with the interaction term. Interaction between the size and time was also tested based on the statistical significance of the interaction term in the ANOVA analyses. The assumptions (homogeneity of variance and normality) were tested before the ANOVA analyses. For post-hoc multiple comparison, Duncan’s multiple range test was performed for comparison among size groups and time points. Statistical differences were determined at a 0.05 probability level, and all results were denoted as mean±SE of the mean unless noted otherwise.

RESULTS AND DISCUSSION

The seawater challenge (direct transfer to seawater) test has been widely considered as a good indicator of seawater adaptability of juvenile salmonids (Wagner, 1974; Clarke, 1982; Johnsson & Clarke, 1988; Madsen & Naamansen, 1989; Bystriansky et al., 2006). The seawater adaptability of under-yearling steelhead trout was evaluated by determining the plasma Na\(^+\) and Cl\(^-\) levels, muscle moisture, and gill NKA activity for 96 h after direct transfer to seawater. Despite the minimal mortality of all size groups, other parameters showed significant effects of size group and time (0, 24, 48, and 96 h) after transfer.

1. Mortality

The average body weight, mortality, and water parameters during the 96 h seawater challenge test are presented in Table 1. The overall mortality was minimal (Table 1). No mortality was observed in the 100 g weight group, while mortality in both the 50 and 150 g weight groups was 2.6% (Table 1). In a previous study of a landlocked O. mykiss strain, Gorie (1993) reported a 29% mortality in the 50 g size class compared to 3% and 6% mortality in 100 and 150 g size classes, respectively, 96 h after seawater transfer. In comparison with the previous study by Gorie (1993), under our experimental conditions the current mortality results after seawater transfer indicate that steelhead trout has a higher tolerance to seawater (32 ppt) than landlocked O. mykiss of the same
size. This agrees with the 96-h LC50 salinity test results reported by Johnsson & Clarke (1988). The current low mortality in steelhead trout suggests that 50 g size fish may have developed at least partial seawater tolerance, which corresponds to the results on development of seawater adaptation in juvenile steelhead trout (Johnsson & Clarke, 1988; Ward & Slaney, 1988; Shin et al., 2011).

2. Plasma Na⁺ and Cl⁻ levels

Plasma Na⁺ and Cl⁻ levels during the 96 h seawater challenge test are presented in Fig. 1. Two-way ANOVA analyses with the interaction terms showed a significant weight group effect ($p<0.05$; Table 2) and a time effect ($p<0.05$; Table 2) but did not show a significant interaction between the weight group and time ($p>0.05$; Table 2) for the both plasma Na⁺ and Cl⁻ concentrations (Fig. 1A & B). Plasma Na⁺ levels in the 50 g size group increased to 180 mmol/L 48 h after the transfer to seawater and reached almost 190 mmol/L after 96 h (Fig. 1A). However, plasma Na⁺ levels in the 100 g size group increased to 165 mmol/L 24 h after seawater transfer and then leveled off later (Fig. 1A). Plasma Na⁺ levels in the 150 g size group increased to about 170 mmol/L 24 h after seawater transfer and then leveled off as well (Fig. 1A). Overall, although plasma Na⁺ levels in both the 100 and 150 g size groups reached a plateau after 24 h after seawater transfer, those in the 50 g size group continued to increase until 96 h (Fig. 1A). Also, the plasma Na⁺ levels in the 50 g size group were significantly higher than those of the 100 or 150 g size groups 96 h after seawater transfer ($p<0.05$, Fig. 1A). Plasma Cl⁻ levels in the 50 g size group rapidly increased to about 150 mmol/L 24 h after the transfer and then gradually increased up to 160 mmol/L after 96 h (Fig. 1B). However, plasma Cl⁻ levels in the 100 g size group increased to around 142 mmol/L 24 h after seawater transfer and then leveled off later (Fig. 1B). Similarly, plasma Cl⁻ levels in 150 g size group reached a plateau after 24 h and then leveled off (Fig. 1B). The plasma Cl⁻ level in the 50 g size group was significantly higher than that in 100 or 150 g size groups 96 h after seawater transfer ($p<0.05$, Fig. 1B).

Bath & Eddy (1979) reported that rainbow trout (mean weight: 13.3 g) did not survive for more than 2 days in seawater (33 ppt), but showed increased mortalities and complete adaptation within 7–10 days after abrupt transfer to two-thirds seawater. Bath & Eddy (1979) concluded that increased plasma Na⁺ and Cl⁻ concentrations in the adaptation phase is the result of initial increased drinking and diffusing of salts into the gills. In a previous study, Gorie (1993) showed that landlocked rainbow trout over 150 g size develop high level hypoosmoregulatory capacity, but trout of 50 and 100 g sizes did not develop a high level. Thus, in comparing the steelhead trout with its landlocked counterpart, steelhead trout seems to develop a higher level of hypoosmoregulatory capacity at a smaller size than landlocked rainbow trout in terms of plasma ionic regulations. The current results on plasma Na⁺ and Cl⁻ level results suggest that while steelhead trout over 100 g size have a high level of hypoosmoregulatory capacity, steelhead trout at 50 g size did not develop a high level of the capacity.

### Table 2. Two-way ANOVA results for the effects of size (weight) and time on plasma Na⁺ and Cl⁻ concentrations, muscle moisture content and gill Na⁺/K⁺ ATPase activity of steelhead trout after direct transfer to seawater

| Source  | DF | Plasma Na⁺ concentration | Plasma Cl⁻ concentration | Muscle moisture content | Gill Na⁺/K⁺ ATPase activity |
|---------|----|----------------------------|--------------------------|------------------------|---------------------------|
|         |    | MS  | F-value | p-value | MS  | F-value | p-value | MS  | F-value | p-value | MS  | F-value | p-value |
| Size    | 2  | 1,196.134 | 7.927  | 0.001   | 1,107.858 | 10.18  | 0.000   | 4.803 | 2.946   | 0.057   | 146.163 | 49.677  | 0.000  |
| Time    | 3  | 2,420.661 | 16.042 | 0.000   | 3,043.333 | 27.966 | 0.000   | 21.611 | 13.256  | 0.000   | 39.056  | 13.274  | 0.000  |
| Size × time | 6 | 169.351 | 1.122  | 0.355   | 176.677 | 1.624  | 0.149   | 3.763 | 2.308   | 0.04    | 7.054   | 2.397   | 0.033  |
| Error   | 96 | 150.891 | 108.822 | 1.63    | 2.942   |
3. Muscle moisture contents

Skeletal muscle moisture contents during the 96 h seawater challenge test are presented in Fig. 2. A two-way ANOVA analysis was performed to test for the main effects of seize and time with the interaction term (Table 2). Muscle moisture contents in the 100 g size group did not show significant decrease during 96 h after the transfer to seawater ($p>0.05$; Fig. 2). However, muscle moisture content in the 150 g size group decreased significantly between 48 h to 96 h after seawater transfer ($p<0.05$; Fig. 2). Moisture contents in 50 g size group rapidly decreased to about 75% 24 h after seawater transfer and did not recover until 96 h ($p<0.05$; Fig. 2). Although there was a significant decrease in muscle moisture contents in the 150 g size group, the percentage of the decrease was relatively small (less than 1.5%) (Fig. 2). Thus, steelhead trout in the 100 and 150 g size groups seem to maintain moisture contents relatively well compared to the 50 g size group. The current results on muscle moisture changes in 50 g steelhead trout after the seawater challenge are comparable to the results on the changes in 150–340 g rainbow trout at the same time after transfer.
to seawater (32 ppt, 13°C) reported by Leray et al. (1981). The rainbow trout in a 200 g size class maintained significantly higher levels of muscle moisture content after the transfer to seawater than did the other smaller size classes (Gorie, 1993). Again, in comparison to the previous studies on rainbow trout reported by Leray et al. (1981) and Gorie (1993), steelhead trout in the current study seem to be able to maintain muscle moisture better than landlocked rainbow trout of the similar size.

4. Gill Na⁺/K⁺ ATPase activity

Gill NKA activity during the 96 h seawater challenge is presented in Fig. 3. Gill NKA activity in the 100 g size group started to significantly increase from 48 h after seawater transfer until the end of test (Fig. 3). Gill NKA activity in the 50 and 150 g size groups did not show significant increases until 96 h after the transfer (Fig. 3). Gill NKA activity in the 100 g size group was significantly higher than that of the 50 and 150 g size groups 24, 48, and 96 h after seawater transfer ($p<0.05$, Fig. 3). Seawater adaptation capacity increased with the increase in the size of juvenile *O. mykiss* (Conte & Wagner, 1965; Wagner, 1974; Johnsson & Clarke, 1988). *O. mykiss* that develop high hypoosmoregulatory capacity are also known to possess the ability to upregulate NKA allowing them to pump out excess Na⁺ and Cl⁻ in response to increment of environmental salinity (Bystriansky et al., 2006; Kennedy et al., 2007). In the current study, 100 g size steelhead trout showed high seawater adaptability by increasing NKA levels in response to the direct transfer to seawater, whereas 50 g size steelhead did not show any upregulation of NKA levels, which in turn suggest an underdeveloped seawater adaptability of 50 g size steelhead trout (Bystriansky et al., 2006; Kennedy et al., 2007). On the other side, steelhead trout of the 150 g size showed the overall lower NKA levels than those of the other size groups and did not show any increase of NKA level in response to seawater transfer (Fig. 3), which can be attributed to the previous finding that the development of capacity to upregulate gill NKA to distinct high levels for hypoosmoregulation is related to growth rate (Ewing et al., 1980). Ewing et al. (1980) reported that a growth rate of less than 0.027 cm/day can prohibit a peak of gill NKA activity in Chinook salmon. In the current study, three seawater tests for each size group were separately conducted in chronological order as described in
the material and method section. Steelhead trout in the 150 g size showed a much lower grow rate compared to the other two size groups, which may be why the gill NKA activity was much lower compared to the other groups and did not respond to the abrupt salinity change in the present study.

In conclusion, in the consideration of plasma Na’ and Cl– levels, muscle moisture content, gill Na+/K+ ATPase activity, and mortality, steelhead trout of 50 g size were found to have not yet developed a high level of hypoosmoregulatory capacity, whereas fish of 100 and 150 g sizes showed a high level of hypoosmoregulatory capacity after direct transfer to seawater (32 ppt). Therefore, steelhead trout larger than a 100 g size is recommended for transfer to seawater culture. In the future, study on optimization of acclimation method (regime) warrant further research.

REFERENCES

Austreng E, Storebakken T, Åsgård T (1987) Growth rate estimates for cultured Atlantic salmon and rainbow trout. Aquaculture 60:157-160.

Bath RN, Eddy FB (1979) Salt and water balance in rainbow trout (Salmo gairdneri) rapidly transferred from fresh water to sea water. J Exp Biol 83:193-202.

Björnsson BT, Stefansson SO, McCormick SD (2011) Environmental endocrinology of salmon smoltification. Gen Comp Endocrinol 170:290-298.

Boeuf G (1993) Salmonid smolting: A pre-adaptation to the oceanic environment. In: Rankin JC, Jensen FB (eds), Fish Ecophysiology, Vol. 9. Chapman and Hall, London, UK, pp 105-136.

Bystriansky JS, Richards JG, Schulte PM, Ballantyne JS (2006) Reciprocal expression of gill Na+/K+-ATPase α-subunit isoforms α 1a and α 1b during seawater acclimation of three salmonid fishes that vary in their salinity tolerance. J Exp Biol 209:1848-1858.

Clarke WC (1982) Evaluation of the seawater challenge test as an index of marine survival. Aquaculture 28:177-183.

Conte FP, Wagner HH (1965) Development of osmotic and ionic regulation in juvenile steelhead.
trot Salmo gairdneri. Comp Biochem Physiol 14:603-620.
Ewing RD, Johnson SL, Pribble HJ, Lichatowich JA (1979) Temperature and photoperiod effects on gill (Na + K)–ATPase activity in Chinook salmon (Oncorhynchus tshawytscha). J Fish Res Board Can 36:1347-1353.
Ewing RD, Pribble, HJ, Johnson, SL, Fustish CA, Diamond J, Lichatowich JA (1980) Influence of size, growth rate, and photoperiod on cyclic changes in gill (Na+K)-ATPase activity in Chinook salmon (Oncorhynchus tshawytscha). Can J Fish Aquat Sci 37:600-605.
Gorie S (1993) Relationship between seawater adaptability and body weight in 0+ landlocked rainbow trout. Nippon Suisan Gakkaishi 59:487-491.
Hawkins GS, Galvez F, Goss GG (2004) Seawater acclimation causes independent alterations in Na'/K'– and H'–ATPase activity in isolated mitochondria-rich cell subtypes of the rainbow trout gill. J Exp Biol 207:905-912.
Hoar WS (1976) Smolt transformation: Evolution, behavior, and physiology. J Fish Res Board Can 33:1233-1252.
Hoar WS (1988) The physiology of smolting salmonids. In: Hoar WS, Randall DJ (eds), Fish Physiology. Vol. 11B. Academic Press, New York, NY, pp 275-343.
Houston AH (1961) Influence of size upon the adaptation of steelhead trout (Salmo gairdneri) and chum salmon (Oncorhynchus keta) to sea water. J Fish Res Board Can 18:401-415.
Johnsson J, Clarke WC (1988) Development of seawater adaptation in juvenile steelhead trout (Salmo gairdneri) and domesticated rainbow trout (Salmo gairdneri)—Effects of size, temperature and photoperiod. Aquaculture 71:247-263.
Kendall NW, McMillan JR, Sloat MR, Buehrens TW, Quinn TP, Pess GR, Kuzishchin KV, McClure MM, Zabel RW (2015) Anadromy and residency in steelhead trout (Oncorhynchus mykiss): A review of the processes and patterns. Can J Fish Aquat Sci 72:319-342.
Kennedy BM, Gale WL, Ostrand KG (2007) Relationship between smolt gill Na’, K’ ATPase activity and migration timing to avian predation risk of steelhead trout (Oncorhynchus mykiss) in a large estuary. Can J Fish Aquat Sci 64:1506-1516.
Kültz D (2015) Physiological mechanisms used by fish to cope with salinity stress. J Exp Biol 218:1907-1914.
Leray C, Colin DA, Florentz A (1981) Time course of osmotic adaptation and gill energetics of rainbow trout (Salmo gairdneri) following abrupt changes in external salinity. J Comp Physiol 144:175-181.
Madsen SS, Naamansen ET (1989) Plasma ionic regulation and gill Na'/K'-ATPase changes during rapid transfer to sea water of yearling rainbow trout, Salmo gairdneri: Time course and seasonal variation. J Fish Biol 34:829-840.
McCormick SD (1993) Methods for nonlethal gill biopsy and measurement of Na’, K’-ATPase activity. Can J Fish Aquat Sci 50:656-658.
McCormick SD, Saunders RL (1987) Preparatory physiological adaptations for marine life of salmonids: Osmoregulation, growth, and metabolism. Am Fish Soc Symp 1:211-229.
Morro B, Balseiro P, Albatal A, Pedrosa C, Mackenzie S, Nakamura S, Shimizu M, Nilsen TO, Sweier H, Ebbesson LO, Handeland, SO (2019) Effects of different photoperiod regimes on the smoltification and seawater adaptation of seawater-farmed rainbow trout (Oncorhynchus mykiss): Insights from Na’, K’–ATPase activity and transcription of osmoregulation and growth regulation genes. Aquaculture 507:282-292.
Moyle PB (2002) Inland Fishes of California. University of California Press, Berkeley, CA.
Prunet P, Boeuf G (1985) Plasma prolactin level during transfer of rainbow trout (Salmo gairdneri)
and Atlantic salmon (*Salmo salar*) from fresh water to sea water. Aquaculture 45:167-176.

Quinn TP, Myers KW (2004) Anadromy and the marine migrations of Pacific salmon and trout: Rounsefell revisited. Rev Fish Biol Fish 14:421-442.

Riley WD, Ibbotson AT, Maxwell DL, Davison PI, Beaumont WRC, Ives MJ (2014) Development of schooling behavior during the downstream migration of Atlantic salmon *Salmo salar* smolts in a chalk stream. J Fish Biol 85:1042-1059.

Shin J, Lee CH, Jo M, Hong KE, Kim DS, Sohn YC (2011) Changes in prolactin and growth hormone gene expression of rainbow trout *Oncorhynchus mykiss* adapted to seawater. Korean J Fish Aquat Sci 44:225-231.

Varunsky VS, Basov YS, Rostomova SA (1991) Seawater adaptability of pink salmon (*Oncorhynchus gorbuscha*) fry: Effects of size and temperature. Aquaculture 99:355-363.

Wagner HH (1974) Seawater adaptation independent of photoperiod in steelhead trout (*Salmo gairdneri*). Can J Zool 52:805-812.

Ward BR, Slaney PA (1988) Life history and smolt-to-adult survival of Keogh river steelhead trout (*Salmo gairdneri*) and the relationship to smolt size. Can J Fish Aquat Sci 45:1110-1122.

Xiong Y, Dong S, Huang M, Li Y, Wang X, Wang F, Ma S, Zhou Y (2020) Growth, osmoregulatory response, adenine nucleotide contents, and liver transcriptome analysis of steelhead trout (*Oncorhynchus mykiss*) under different salinity acclimation methods. Aquaculture 520:734937.

Xiong Y, Wang X, Dong S, Wang F, Yang J, Zhou Y (2019) Comparisons of salinity adaptation in terms of growth, body composition, and energy budget in juveniles of rainbow and steelhead trouts (*Oncorhynchus mykiss*). J Ocean Univ China 18:509-518.