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Differential survival of juvenile sockeye and coho salmon exposed to low dissolved oxygen during winter

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ABSTRACT

Juvenile sockeye salmon (length: 43-78 mm) survived 100% for 24 h in cages in ice-covered Black Lake, Alaska at oxygen concentrations >65% (9.0 mg l^{-1}), but only 45% at 24% saturation (3.0-3.3 mg l^{-1}) and none at <17% saturation (2.3 mg l^{-1}). All juvenile coho (length: 50-120 mm) survived 100% for 24 h down to 21% oxygen saturation (3.1 mg l^{-1}), and all 50 coho survived 4-5 days at 23-24% saturation (3.2-3.3 mg l^{-1}).

Key Words: Oncorhynchus, nerka, kisutch, oxygen, winter, habitat, Alaska

INTRODUCTION

Adequate dissolved oxygen in water is critical to fish populations and considerable research has been conducted on the physiology of oxygen uptake and oxygen requirements of fishes. Fishes may respond to reduced oxygen concentrations through physiological changes, including elevation in both rate and amplitude of breathing, decreased heart rate, increased stroke volume of the heart (Randall & Smith, 1967) and altered metabolic rate (Brett, 1964; Waller et al., 1997). Alternatively, fishes might respond behaviorally to low oxygen concentrations by avoiding such regions (Priede et al., 1988; Kramer, 1987; Spoor, 1990) or stopping their migration (Alabaster, 1989). Low oxygen concentrations have been shown to influence performance characteristics of fishes, including growth rate, food conversion efficiency, feeding and swimming performance (Herrmann et al., 1962; Dahlberg et al., 1968; Jones, 1971; Davis, 1975; Farrell et al., 1998). Oxygen concentrations resulting in mortality typically occur at much lower concentrations than those causing sublethal effects, indicating oxygen concentrations can affect fishes over a range of concentrations.

During an extensive review of oxygen requirements for aquatic life, Davis (1975) developed oxygen criteria for species groups at three levels of protection. For freshwater salmonids, the oxygen content criteria ranged from 7.75 mg l^{-1} to 6.00 mg l^{-1} to 4.25 mg l^{-1}, which represented protection levels ranging from a high level of safety to some risk for a portion of the population to significant risk to a major portion of the population. These criteria equate to percentage oxygen saturation values of 76%, 57%, and 38%, respectively, at temperatures between 0°C and 10°C, then increasing to 85% to 46% at 20°C.

However, few studies have been conducted that describe responses of Pacific salmon Oncorhynchus spp. to low oxygen concentrations during winter. Winterkill is common in shallow lakes supporting resident salmonids (Northcote & Larkin, 1956; Ashley et al., 1992) and warmwater fishes (Barica & Mathias, 1979; Hall & Ehlinger, 1989), but it is rarely described in lakes producing anadromous salmonids.

Sockeye salmon Oncorhynchus nerka (Walbaum) runs to Black Lake on the Alaska Peninsula fluctuate more than runs to nearby Chignik Lake and other lakes in Southwestern Alaska. Black Lake is shallow (mean depth <1.4 m during winter) but moderately large (41 km^2) and research in recent years has focused on environmental factors that influence run size fluctuations (range: 0.3 to 3.5 million adult sockeye salmon per year since 1975). Low oxygen has been measured in Black Lake during winter (Ruggerone, 1992). Sampling of salmon under the ice indicated that juvenile sockeye salmon might tolerate low oxygen concentrations less than juvenile coho salmon O. kisutch (Walbaum), because coho salmon were typically captured in low oxygenated water near the bottom, whereas most sockeye emigrated to nearby Chignik Lake, which is deep (mean depth: 26 m) and saturated with oxygen (>90%) to 40 m or more.

This investigation aimed to quantify the survival of juvenile sockeye and coho salmon exposed to low oxygen concentrations in Black Lake, Alaska.

METHODS

Survival of juvenile sockeye and coho salmon exposed to low dissolved oxygen was tested in Black Lake (56° 16'N Latitude, 158° 50'W Longitude) on the Alaska Peninsula during February 1992 and 1995. Juvenile sockeye salmon (mean length: 67 mm, range 43-78 mm) were captured by baited minnow traps in nearby Chignik Lake, then transported approximately 10 km in 19 l, aerated containers to Black Lake. Juvenile coho salmon (mean length: 88 mm, range: 50-120), which were not readily available in Chignik Lake, were captured by baited minnow traps in Black Lake and transported in 19 l containers to the study location. Care was given during transportation to minimize potential stress and to maintain high oxygen concentrations. All transported salmon were in good condition at the start of the tests.

At the study site, 10-20 sockeye or coho salmon were placed in wire-mesh cages (6.4 mm^2 mesh, 46 cm x 23 cm), then lowered to one of several depths under the ice (up to 3.5 m) in order to expose fish to a range of oxygen concentrations. Dissolved oxygen (mg l^{-1} and %) and temperature were measured at each cage using an Orion Model 840 dissolved oxygen meter after calibration. Fish were held in the cages for 24 h, then examined for survival.

In addition to these experimental tests, oxygen concentrations were measured at several locations in Black Lake where juvenile coho salmon were captured in traps set over night. These data were used to provide additional information regarding the tolerance of juvenile coho to low oxygen concentrations.

RESULTS

Totals of 264 sockeye salmon and 145 coho salmon were tested for tolerance to low dissolved oxygen in Black Lake. Dissolved oxygen concentrations at the test site ranged from 6.0-100% (0.9-14.2 mg l^{-1}) and water temperature ranged from 0.4 °C to 2.7 °C.

Oxygen tolerance tests in Black Lake indicated that sockeye salmon have lower survival in water containing little dissolved oxygen compared to coho salmon. Survival of sockeye salmon during the 24 h period was 100% when the water exceeded 65% oxygen or 9.0 mg l^{-1} (Fig. 1). Sockeye survival declined to 90-97% as oxygen content declined from 65% to 34% (4.5-9.0 mg l^{-1}), then survival declined rapidly as oxygen content declined below 30% saturation (4 mg l^{-1}). At 24% saturation (3.0-3.3 mg l^{-1}), 45% of sockeye salmon survived. No sockeye salmon survived the brief exposure to oxygen concentrations below 17% saturation (2.3 mg l^{-1}).

In comparison, all coho salmon survived 24 h exposure to oxygen concentrations as low as 21% of oxygen saturation (3.1 mg l^{-1}). Furthermore, all 50 coho survived after being held for 4-5 days at 23-24% saturation (3.2-3.3 mg l^{-1}).

All 22 coho captured in traps near the lake bottom and held overnight in Black Lake survived exposure low oxygen. Eight coho were exposed to water containing 13-20% oxygen (1.6-3.2 mg l^{-1}) and 14 coho were exposed to 21-27% oxygen (2.8-3.6 mg l^{-1}).

DISCUSSION

This investigation compared survival of juvenile sockeye and coho salmon exposed to low oxygen during winter conditions. Juvenile coho and sockeye salmon can tolerate brief (24 h) exposure to oxygen concentrations that exceed 65% saturation (9.0 mg l^{-1}) without mortality. However, survival of coho and sockeye differed significantly as oxygen content declined below 65%. Coho salmon experienced no mortality in oxygen concentrations down to 21% oxygen saturation (3.1 mg l^{-1}), whereas significant mortality of sockeye began near 30% saturation. These data indicate survival in low oxygen environments may differ among salmonids.

The greater tolerance of coho to low oxygen compared with sockeye may reflect differences in habitat typically occupied by the two species. Sockeye typically inhabit relatively deep, oligotrophic lakes that have high oxygen content, whereas coho can inhabit marginal habitats such as small, off-channel areas where oxygen concentration can become low.

In the Chignik watershed, the greater tolerance of low dissolved oxygen shown by coho compared with sockeye salmon is consistent with other observations in the lakes. For example, coho salmon are captured most frequently near the lake bottom in Black Lake during winter where oxygen concentrations are lowest but temperatures are highest (Ruggerone, 1992). In contrast, most juvenile sockeye emigrate from Black Lake during late fall and winter and overwinter in the deep, oxygen-saturated Chignik Lake. The emigration of sockeye salmon suggests sockeye may be less able to acclimate to the low oxygen concentration in Black Lake.

Although winterkill conditions can affect many resident salmonid populations in some areas (e.g., interior British Columbia, Northcote & Larkin, 1956, Ashley et al., 1992), winterkill is not common to most anadromous Pacific salmon populations. Few major salmon populations, especially sockeye salmon that typically inhabit lakes for one or two years, are associated with shallow lakes that experience low oxygen during winter. Nevertheless, Black Lake and several small shallow lakes on Kodiak Island represent productive sockeye salmon lakes that can be influenced by hypoxic conditions during winter.

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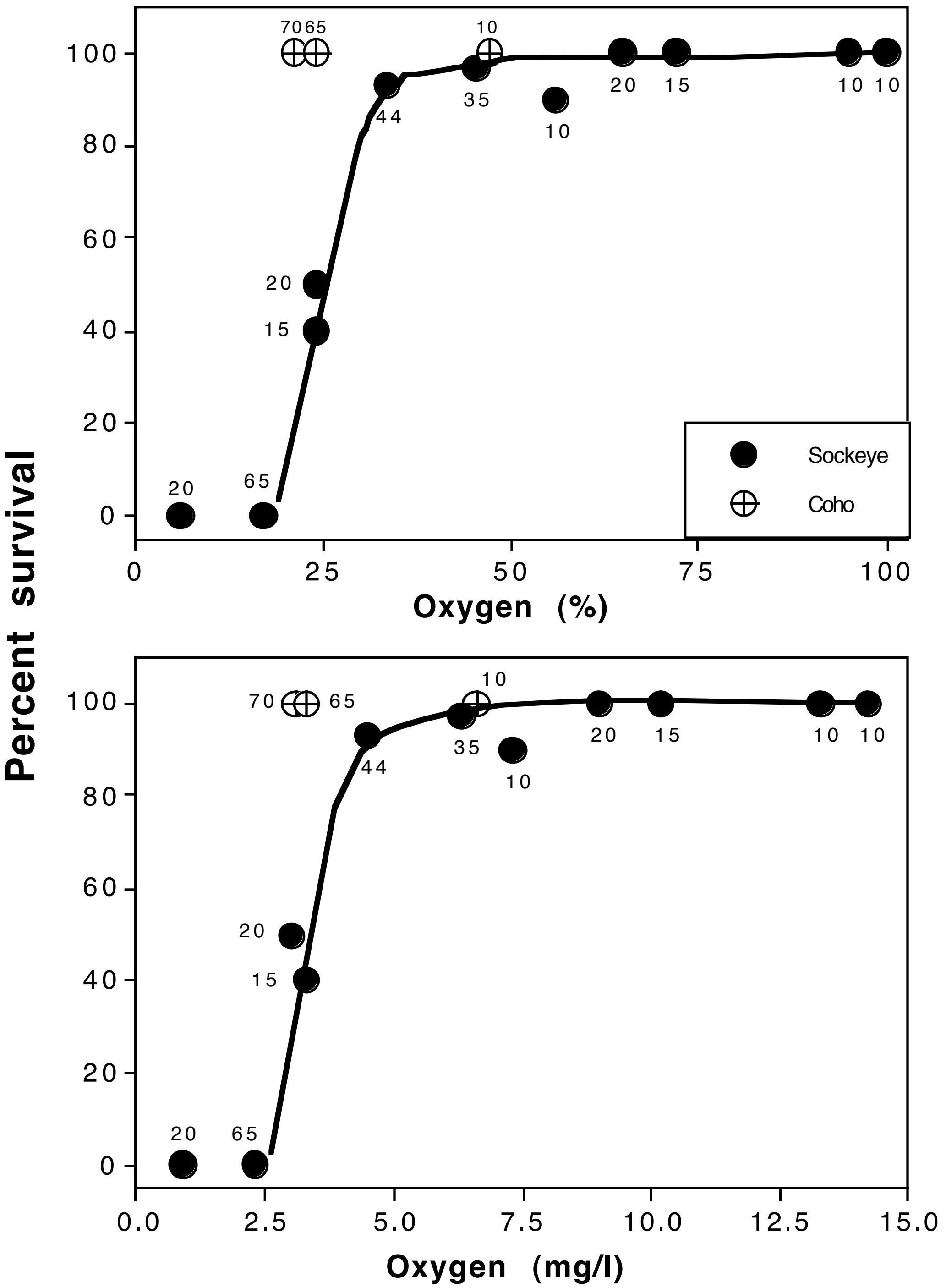

Fig 1. Survival of juvenile sockeye and coho salmon in Black Lake at oxygen concentrations ranging from to 6% to 100% saturation (upper graph) and 0.9 to 14.2 mg l^{-1} (lower graph). All salmon were held in cages and re-examined 24 hours later. Samples size is shown adjacent to each value. Line drawn by hand.