EFFECTS OF ACIDITY AND ALUMINUM ON THE PHYSIOLOGY AND MIGRATORY BEHAVIOR OF ATLANTIC SALMON SMOLTS IN MAINE, USA

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Abstract. Atlantic salmon, *Salmo salar*, smolts of hatchery origin were held for 5 to 16 days in ambient (pH 6.35, labile Al = 60 μg L^{-1}), limed (pH 6.72, labile Al = 58.4 μg L^{-1}), or acidified (pH 5.47, labile Al=96 μg L^{-1}) water from the Narraguagus River in Maine, USA. Wild smolts were captured in the same river in rotary traps and held for up to two days in ambient river water. Osmoregulatory ability was assessed by measuring Na^+/K^+ ATPase activity, hematocrit, and blood Cl concentration in freshwater, and after 24-hr exposure to seawater. Hatchery smolts exposed to acidic water and wild smolts displayed sub-lethal ionoregulatory stress both in fresh and seawater, with mortalities of wild smolts in seawater. Using ultrasonic telemetry, hatchery-reared ambient and acid-exposed, and wild smolts were tracked as they migrated through freshwater and estuarine sections of the river. The proportion of wild smolts migrating during daylight hours was higher than for hatchery-reared smolts. Wild smolts remained in the freshwater portions of the river longer than either group of hatchery smolts, although survival during migration to seawater was similar for all three treatments. Acid-exposed hatchery-origin and wild Narraguagus River smolts were both under ionoregulatory stress that may have affected their migratory behavior, but not their survival for the time and area in which we tracked them.

Key words: acid, aluminum, Atlantic salmon, behavior, osmoregulation, survival

1. Introduction

Atlantic salmon formerly occurred in nearly every river system in the U.S.A. north of the Hudson River, and annual returns are estimated to have been 300,000-500,000 fish. Reproducing stocks now exist in only seven rivers in Maine, and annual returns have declined to less than 50 in 1998 (USFWS, 1999). Harvest has been greatly reduced and the rivers are stocked with hatchery-produced fish, but populations have failed to increase. Atlantic salmon populations have been reduced by acidic deposition in Nova Scotia, Canada (Lacroix, 1989) and Norway (Hesthagen and Hansen, 1991), however in previous investigations we were unable to demonstrate significant mortality of river-resident life stages of Atlantic salmon in Maine rivers due to acidity (Haines *et al.*, 1990). Recently, Staurnes *et al.* (1996) demonstrated that short-term exposure to acidic water reduces subsequent marine survival of Atlantic salmon smolts. We investigated the effects of acidic water and aluminum on the physiology and migratory behavior of Atlantic salmon smolts in the Narraguagus

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River, Maine. We hypothesized that exposure to acidified water would cause osmotic stress, leading to a change in migratory behavior and a decrease in survival during seaward migration.

2. Materials and Methods

Atlantic salmon returns in the Narraguagus River have declined from 100-200 in the 1970s to 20-30 in the 1990s (USFWS, 1999). The river is low in acid neutralizing capacity (ANC <150 μeq L^{-1}); pH is typically 6-7 with seasonal depressions to <5 (Haines *et al.,* 1990). During this study the pH gradually increased from about 5.7 to about 6.5 and was below pH 6 from 4 March to 13 April, with one depression to pH 4.95 on 12 March. For the physiology study, smolts were held in four, 385 L plastic streamside tanks located approximately 10 km upstream of the head-of-tide. Two tanks received ambient river water, one ambient water with $NaHCO_3$ added (target pH range 6.5-7.0), and one ambient water with acid and aluminum added (target pH range 5.0-5.5; target labile Al (LAl) concentration 150-200 μg L^{-1}). Chemicals were added by slow drip from stock solutions into a mixing chamber with a retention time of 14 min. River-produced smolts (N=30, 2 year olds, from either natural reproduction or stocking of hatchery-produced fry) were captured using rotary-screw traps (Thedinga *et al.*, 1994) and were placed in one ambient water tank. One-year-old smolts of Penobscot River stock (mean total length ± 1SE = 19.15 ± 2.73 cm; mean weight ± 1SE = 67.27 ± 2.74 g; n=24) were obtained from the Green Lake National Fish Hatchery in Ellsworth, Maine and 50 each were placed in ambient, limed, and acidified tanks. Hatchery fish were determined to be smolts by coloration and morphological characteristics; river-resident smolts were captured during downstream migration in the middle of the annual smolt migration.

Exposure of smolts to treatment water (FW) began on 7 May. Three to five smolts were sampled at random from all tanks on 16 May. Smolts were anesthetized with enough buffered MS-222 to immobilize them within two minutes. Removal of gill tissue and determination of gill Na^+/K^+ ATPase activity was done by the methods of McCormick (1993). Smolts were bled from the caudal vein and hematocrit read immediately from centrifuged blood. The remaining blood was centrifuged at 1,000 G for 3 minutes, and the serum was removed and frozen at -20°C. Serum chloride concentration was determined by ion chromatography. Plasma thyroxine (T_4) concentration was measured by radioimmunoassay (Dickhoff *et al.*, 1978 as modified by Specker *et al.*, 1989). A seawater (SW) challenge test was then conducted using modified methods of Clarke (1982).

Smolt migratory behavior was monitored with the use of surgically implanted ultrasonic transmitters (Lacroix and McCurdy, 1996) and stationary receivers in the river system (Figure 1). Hatchery and wild smolts were released in groups of 3 to 5 on three occasions between 10 and 16 May, and were tracked until 28 May.

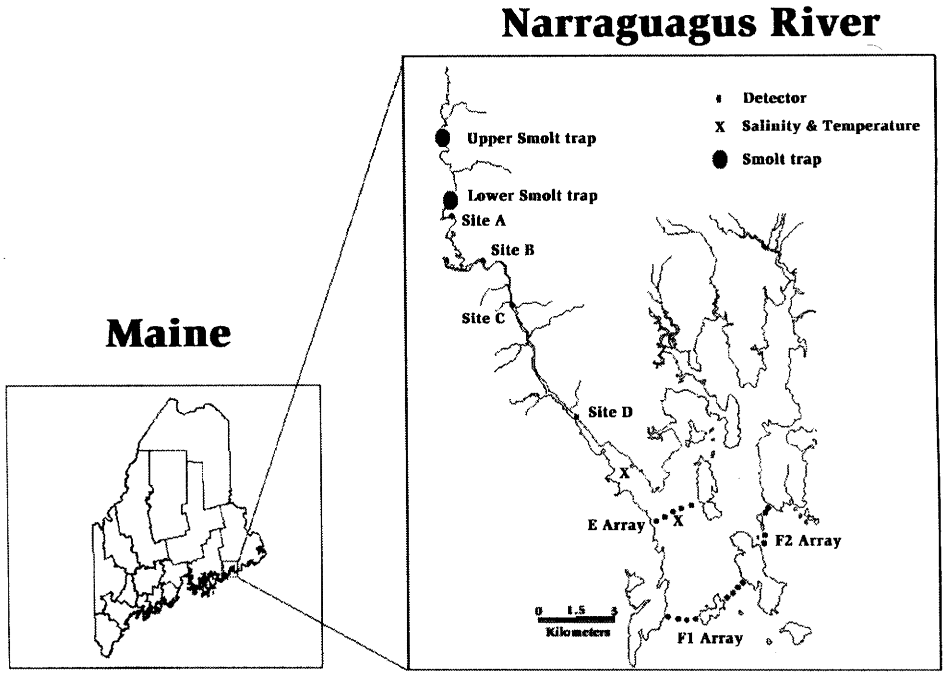

Figure 1. Map showing location of study area.

All water chemical analyses were done by standard methods (USEPA, 1987). Mann-Whitney tests were used to determine differences between treatments in residence time in each section of the river. Rayleigh's test was used to determine if movement of smolts was random with respect to time of day or tidal cycle (Batschelet, 1981), and standard deviations were calculated by the method of Mardia (1972). The Watson-Williams test was used to determine differences between treatments with respect to time of movement (Batschelet, 1981). Mortality in each river section was estimated using the Mark computer program with the Cormack-Jolly-Seber model (White, 1998).

3. Results

No hatchery-reared smolts from any treatment died in FW or SW, but after 24 h in SW one wild smolt died, one was immobile, and one could not remain upright. Wild smolts had significantly greater gill Na^+/K^+ ATPase activity than hatchery smolts in both FW and SW (Figure 2). There were few significant differences in plasma Cl, with hatchery fish from the limed treatment being higher in FW. Hematocrit and plasma thyroxine concentrations did not differ between treatments.

There were clear differences between hatchery and wild smolts for the residence time in FW (Table 1). Wild smolts remained in FW significantly longer than for ambient smolts but not acid-exposed smolts. Only 46% (12) of

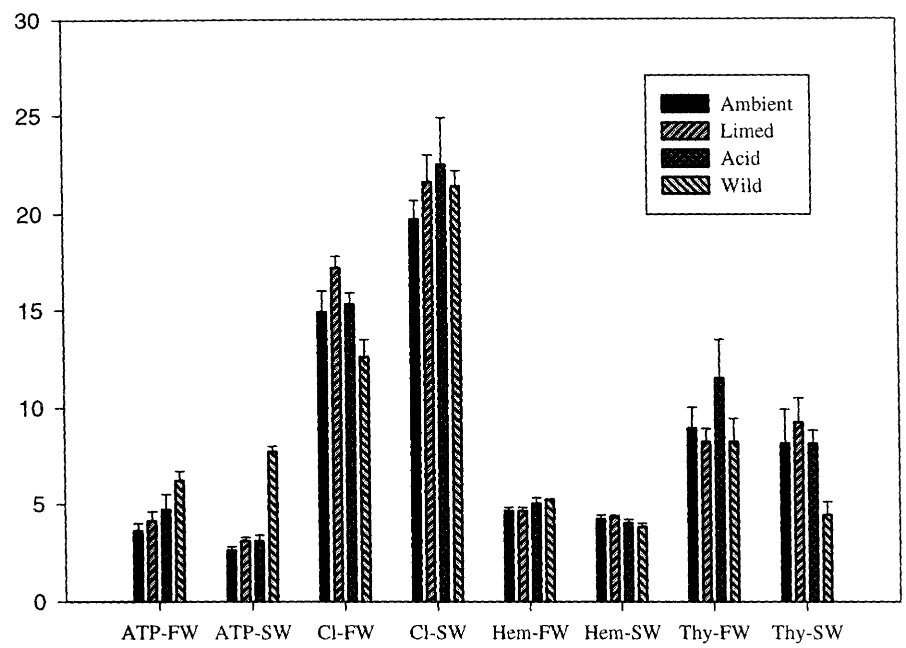

Figure 2. Physiological response of fish to the treatments. FW=fresh water; SW=salt challenge; ATP=Na/K ATPase (umol/mg/h); Cl=plasma Cl (meq/L/10); Hem=hematocrit (%/10; Thy=plasma thyroxine (ng/mL). Units are in parentheses.

TABLE I

Residence time of smolts in each river section. Mann-Whitney tests were used to determine significance ($p<0.05$). Treatments with the same letter are not significantly different from each other. Amb=ambient river water; Est=estuary.

Treat-ment	Residence Time in days (mean ± 1SE; number of observations ranged from 8 to 26)				
	Freshwater	Upper Est	Middle Est	Lower Est	Total
Amb	0.53 ± 0.11^{a}	0.58 ± 0.13^{a}	0.43 ± 0.12^{ab}	0.34 ± 0.16^{a}	1.76 ± 0.274^{a}
Acid	0.70 ± 0.20^{ab}	0.89 ± 0.38^{a}	0.23 ± 0.13^{a}	0.28 ± 0.06^{a}	2.43 ± 0.51^{a}
Wild	1.92 ± 0.42^{b}	1.43 ± 0.34^{a}	0.72 ± 0.2^{b}	0.23 ± 0.1^{a}	4.04 ± 0.50^{b}

the wild smolts were able to leave the FW sections in one day, whereas 91% (9) and 82% (8) of the ambient and acid smolts, respectively, did so. The total time wild smolts spent emigrating through the FW and estuarine sections of the river was significantly longer than that for hatchery-reared smolts. There was no correlation between FW and estuarine residence time for fish from any treatment.

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Few hatchery (2 ambient, 2 acid), but many wild (7) smolts moved during the brightest hours of the day while in tidal sections. Smolts moved downstream with low salinity water and encountered high salinities as they moved out of the middle estuary. One ambient (11%), three acid-exposed (33%), and seven wild (29%) smolts returned upstream to near the head of tide (Site C, always fresh water) shortly after entering the middle estuary at site D (varied from fresh water at low tide to 10‰ at high tide). Upstream movements were significantly ($p<0.05$) related to the tidal cycle. Smolts that returned upstream to site C did so with a flood tide (mean time = 10:27 ± 1:47 hrs after high tide). When these smolts successfully left the upper estuary, sunset occurred 1-5 hrs after high tide, and these smolts migrated with the ebb tide. Those movements in which smolts were unsuccessful at leaving the upper estuary were random with respect to time of day and time of tide.

Smolt survival was lowest in the middle estuary (77%), where salinity and temperature fluctuated the most (0-32‰), and greatest in the lower estuary (100%), where salinity and temperature varied less than in other tidal sections (25-32‰). Survival was 96% and 93% in FW and upper estuarine sections respectively. There were no differences in survival between treatments.

4. Discussion

Although wild smolts had higher Na^{+}/K^{+} ATPase activities than hatchery smolts, they were less able to osmoregulate in SW. Three wild smolts died or were moribund in SW, and those that survived had the lowest plasma Cl concentration in FW and the largest increase (70%) in SW. They also had the highest FW and lowest SW hematocrit, respectively. These conditions are characteristic of smolts with impaired osmoregulatory ability (Staurnes *et al.*, 1996). Thyroxine concentrations of smolts in this study were substantially lower than those of hatchery-reared smolts reported in McCormick and Bjornsson (1994). The reasons for this are unknown, but thyroxine can be reduced in wild smolts held in captivity for five days (S. McCormick, personal communication).

Mean residence time of wild smolts in FW was about four times that of ambient and acid smolts, even though these fish were actively migrating when captured. This may be related to differences between hatchery and wild fish in response to handling or surgical stress; however, 12 of the 26 wild smolts left the FW section during the first night after surgery. The majority of smolts in all treatments passed telemetry receivers during an ebb tide, indicating that they take advantage of the strong 'downstream' tidal flow (Moore *et al.*, 1998). Significantly more wild and acid-exposed smolts made large upstream movements from the middle to upper estuary than did ambient smolts. The lower part of the upper estuary section is where the smolts first encounter water of >8‰, and this is the zone of complex aluminum chemistry, which can be even more toxic than in freshwater (Rosseland *et al.*, 1992). If wild smolts were physiologically compromised, their movements upstream at this time may have been in search of a less physiologically stressful environment (lower salinity). Handeland *et al.*

(1996) found that predation rates were higher on smolts suffering from osmoregulatory stress after transfer to SW.

5. Conclusions

Wild smolts that had been exposed to acidic, aluminum-enriched river water were less able to osmoregulate in SW than hatchery smolts, and wild smolts spent more time in the river and made more repeat migrations than hatchery smolts. However, seaward migratory survival of all three treatments did not differ for the time we could track the fish.

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