

## Is solar radiation responsible for declines in marine survival rates of anadromous salmonids that rear in small streams?

Carl Walters and Bruce Ward

**Abstract:** There have been profound declines in marine survival rates of steelhead trout (*Oncorhynchus mykiss*), coho salmon (*O. kisutch*), chinook salmon (*O. tshawytscha*), and Atlantic salmon (*Salmo salar*) since the mid-1980s, and these declines have been particularly acute in sunny regions. We suggest that the problem may originate in freshwater with radiation (e.g., UV-B) damage to metabolic machinery that is expressed during stressful periods of smolting and ocean entry and that progressively worse damage may soon appear as reduction in freshwater survivals as well. This hypothesis can be tested quickly by management agencies by comparing survival rates of hatchery-reared fish with and without radiation protection during rearing.

**Résumé :** Nous observons depuis le milieu des années 80 des baisses graves du taux de survie en mer du saumon arc-en-ciel (*Oncorhynchus mykiss*), du coho (*O. kisutch*), du quinnat (*O. tshawytscha*) et du saumon atlantique (*Salmo salar*). Ces baisses sont particulièrement marquées dans les régions ensoleillées. Nous pensons que le problème trouve son origine en eau douce, le rayonnement (p. ex. les UV-B) causant des dommages métaboliques qui s'expriment pendant les périodes de stress que sont la smoltification et l'entrée en mer, et que des dommages de plus en plus graves pourraient se manifester bientôt sous la forme d'une réduction de la survie en eau douce également. Cette hypothèse peut être vérifiée rapidement par les organismes de gestion : il suffirait de comparer les taux de survie de poissons d'élevage qui seraient protégés ou non du rayonnement pendant le grossissement.

[Traduit par la Rédaction]

### Geographic and temporal patterns in survival

Declines in marine survival rates and recruitment rates per spawner have severely impacted steelhead, coho, chinook, and Atlantic salmon populations throughout the northern hemisphere, from Britain to California (Fig. 1). Many populations in California, Oregon, and Washington are or will soon be listed as endangered. There were major disruptions in B.C. commercial and sport fisheries in 1998 to protect declining coho and steelhead populations. Meanwhile, some lake- and ocean-rearing salmonids like sockeye (*O. nerka*) and pink (*O. gorbuscha*) exhibited good survival during the late 1980s, as did coho in Alaska (Hare et al. 1998). Marine survival rates of many stocks of chinook salmon (*O. tshawytscha*) have declined severely but over a longer time period and for both stream- and ocean-rearing life-history types (Beamish et al. 1997). Despite severe declines in harvest and

high smolt abundances, most Canadian Atlantic salmon stocks (except Newfoundland) have shown some decline in adult abundance (Anonymous 1998).

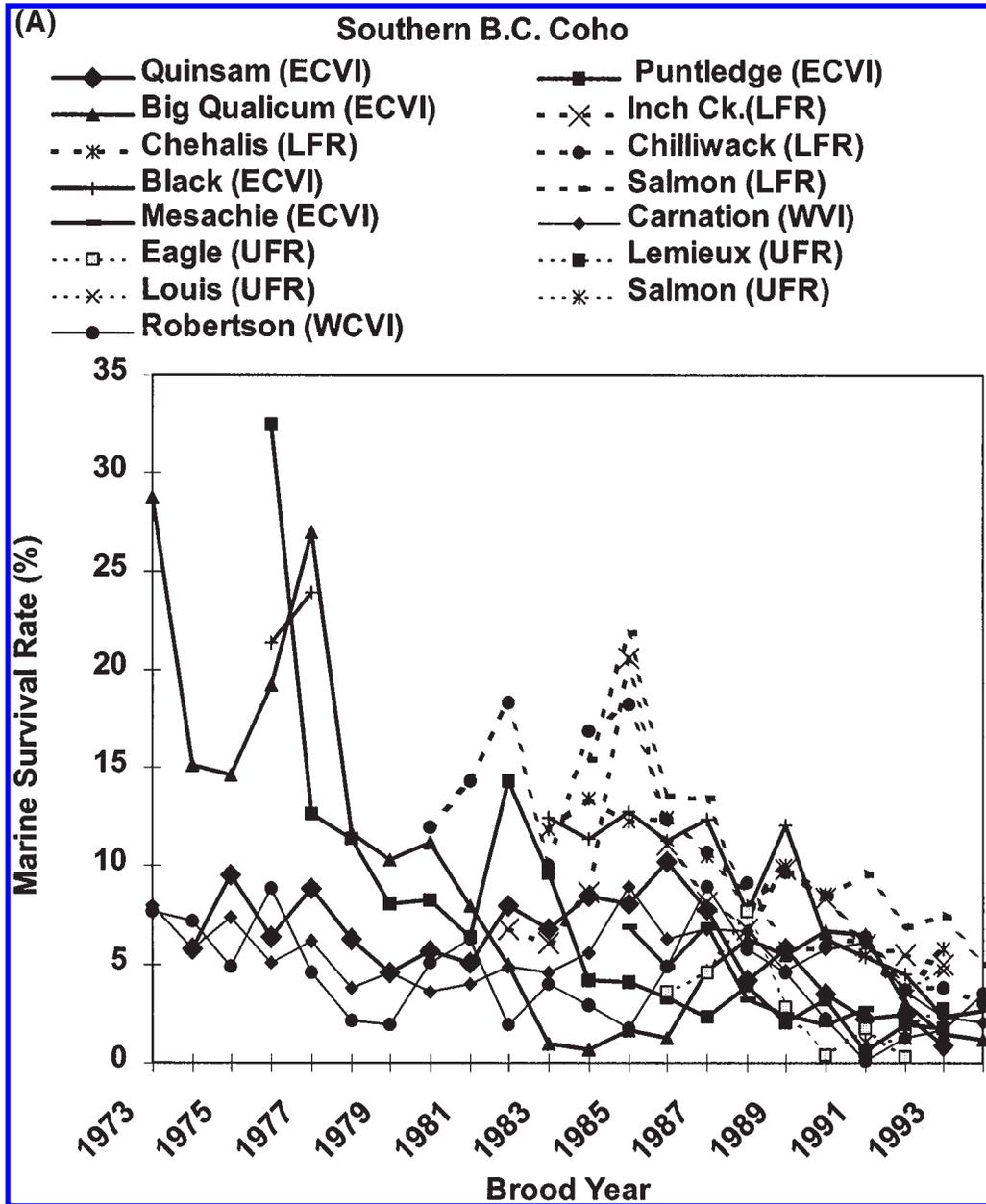
For B.C. coho, where we have data over a variety of freshwater-rearing situations, there is a disturbing correlation between sunlight and the declines. We see differences in trends between interior and coastal populations (declines have been much more severe and started earlier for interior stocks rearing in relatively sunny, rain-shadow areas), southern and northern stocks (southern stocks started declining sooner than stocks from more northerly, wetter regions where very low survivals have been seen only after 1995), and cloudy and sunny regions within the southwestern B.C. coastal region (higher recent survivals in Fig. 1 are for stocks from rainy areas on the west coast of Vancouver Island and the upper Fraser Valley, while survivals are lowest for stocks that rear in the rain-shadow region of eastern Vancouver Island). Trends are similar in wild and hatchery populations. B.C. steelhead sport catch statistics show similar spatial patterns and trends. Mean survival rates over coho stocks from the data in Fig. 1 for 1989–1994 were ordered by region from wet to dry (using mean 1961–1990 rainfall, stations indicated), and an index of change in survival rate was calculated (mean survival for 1989–1994 divided by mean survival for 1973–1988; Table 1).

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C. Walters<sup>1</sup> and B. Ward. Fisheries Centre, The University of British Columbia, Vancouver, BC V6T 1Z4, Canada.

<sup>1</sup>Author to whom all correspondence should be addressed.  
e-mail: walters@fisheries.com

**Fig. 1.** Trends in apparent marine survival rate estimated from coded wire tag returns (B.C. coho), recruits/spawner (R/S) ratios (east coast Atlantic salmon), and direct fence counts of smolts and adults (steelhead). For coho, WCVI = west coast Vancouver Island stock, ECVI = east coast Vancouver Island, LFR = lower Fraser River, UFR = upper (interior) Fraser River, NC = north coast. Sources: coho, Canadian Department of Fisheries and Oceans, PSARC reports; steelhead, Cramer et al. 1998; Atlantic salmon, G. Chaput, DFO Moncton, personal communication.

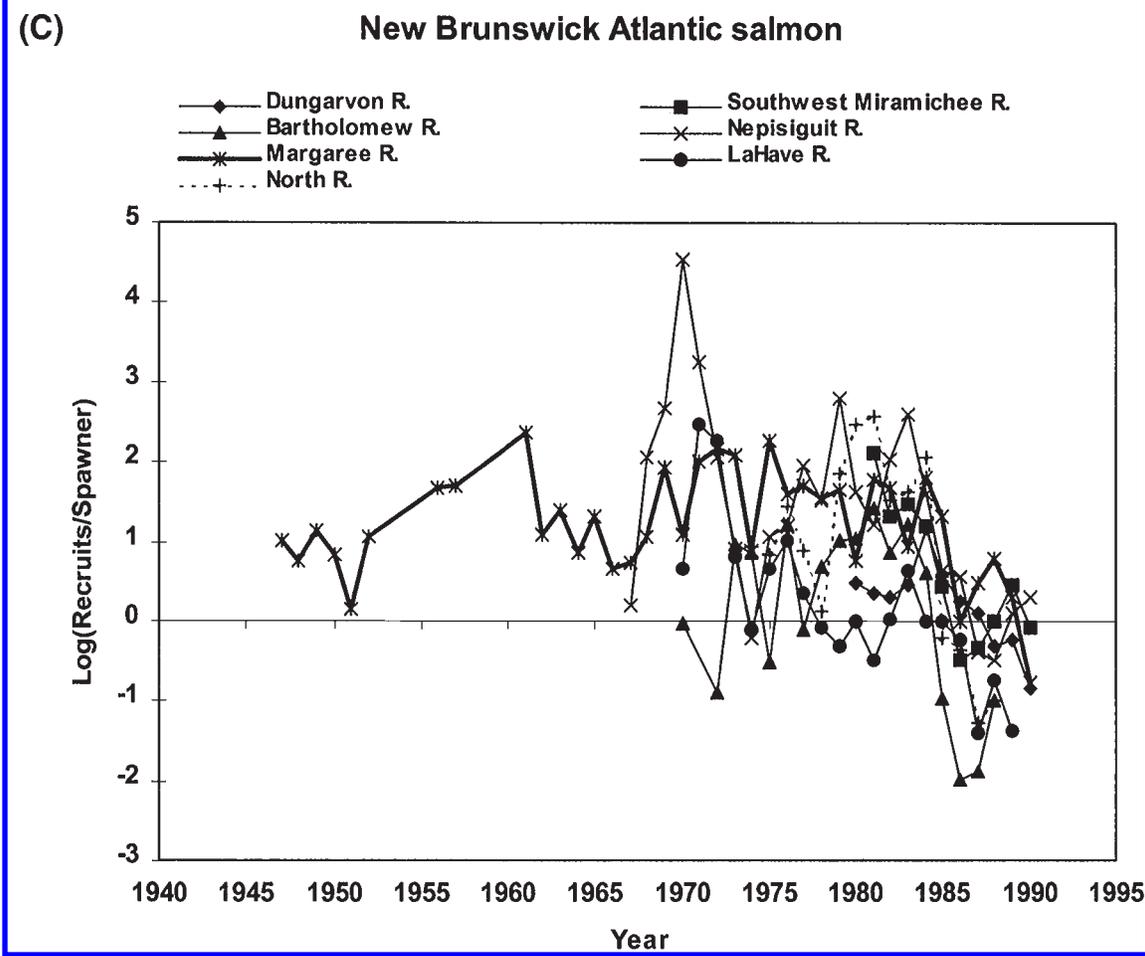
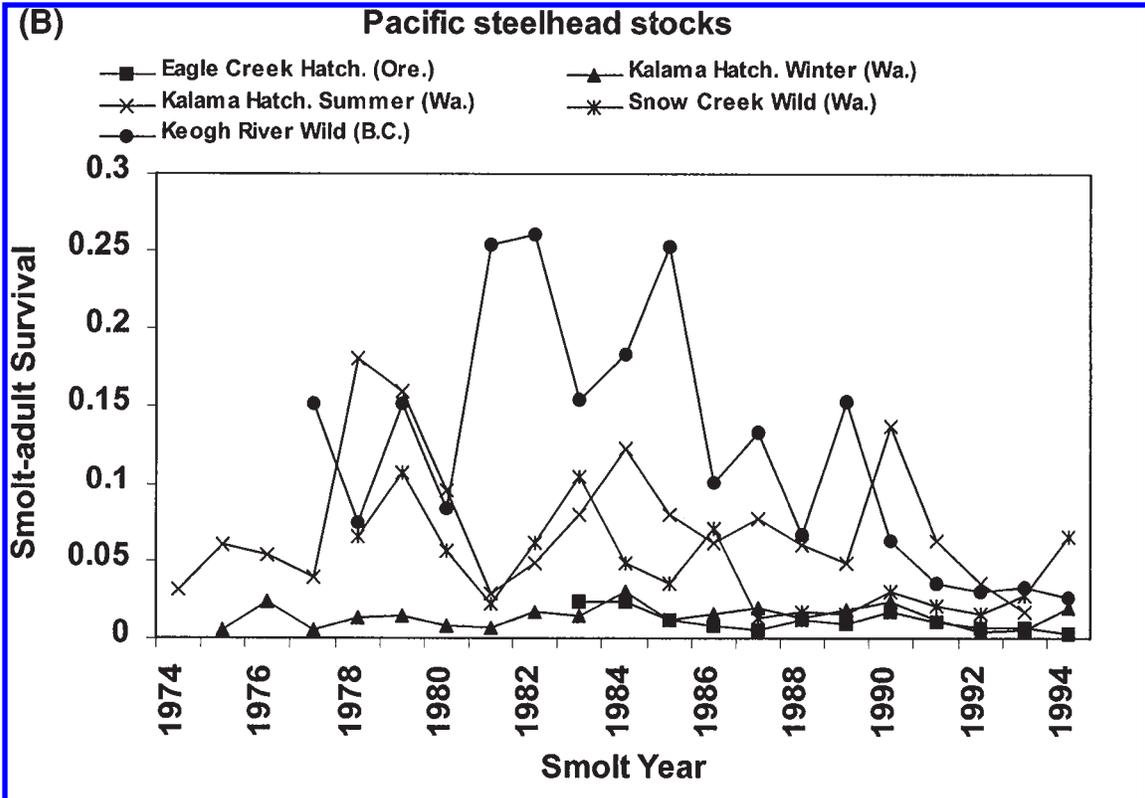


Regions are ordered in terms of relative decrease in survival rate; however, the west coast of Vancouver Island (WCVI) had lower survival rates in earlier years so fared better than the lower Fraser River (LFR) only in terms of relative decrease in survival. The differences in mean survival rate are highly significant (one-way ANOVA, years as repeated measures,  $F_{3,11} = 9.35, P < 0.002$ ), but the differences in survival ratios are not ( $F_{3,8} = 2.84, P = 0.11$ ). Curiously, wild coho stocks from Puget Sound (climatic conditions similar to LFR) have shown considerably higher marine survival rates than those from the adjoining Georgia Strait but with similar downward trends (Beamish et al.

1997; W. Tveit, Washington Department of Fish and Wildlife, unpublished data). Another word of caution is that the east coast Vancouver Island (ECVI) data include one stock (Mesachie) with juveniles that rear in a lake and hence might not be expected to be exposed to radiation patterns as severe as those experienced by stream-reared juveniles.

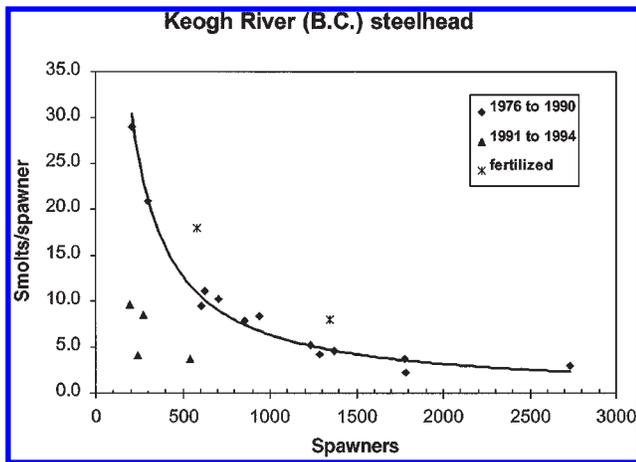
For Atlantic salmon, temporal patterns in direct measures of marine survival rate (as opposed to the overall recruits/spawner trends in Fig. 1) also show geographical differences suggestive of a climatic effect: survival rates for Newfoundland stocks (wet region) declined in the late 1980s but recovered during the 1990s, while survival rates for Quebec

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**Fig. 2.** Recent declines in freshwater survival rates of steelhead trout in the Keogh River, B.C., suggest that earlier declines in marine survival rates are now being followed by freshwater impacts as well (fertilized = smolt yield from years of nutrient addition to the stream).



and New Brunswick (drier regions) declined but have not recovered (Chaput 1997; Chaput et al. 1998). However, even Newfoundland stocks had very low returns in 1997 (Dempson et al. 1998).

Only two major B.C. sockeye populations have collapsed in recent years. The Rivers Inlet, Owikeeno Lake, population is noted for having among the smallest of smolts and for being the only major stock with juveniles that rear only in the top few metres of the lake water column; the lake is extremely turbid with glacial flour (Hyatt et al. 1989). Marine survival rates apparently started declining in the early 1980s in conjunction with a decreasing trend in freshwater flow and smolt size (C. Wood, DFO, personal communication). However, the nearby Long Lake population showed a similar decline, and that lake is not highly turbid. A common "marine effect" is suggested for both stocks.

Patterns are more complex for chinook salmon, which have both ocean-rearing ("fall") and freshwater-rearing ("spring-summer") life-history types. Some fall hatchery stocks showed severe survival declines during the late 1970s, and survivals have remained low since then. In contrast, spring-summer stocks from the B.C. interior and upper Columbia River also had relatively poor recruit/spawner performance during the mid-1970s but then had a period of higher survival, followed in the early to middle 1980s with severe declines similar to those shown for other species in Fig. 1 (Bradford 1994; Deriso et al. 1996). Analytical methods for recruit/spawner analysis developed by Deriso et al. appear to effectively separate effects of changes in "marine survival" from effects of freshwater changes in adult abundance and various water management (dams, etc.) factors in the Columbia. Considering that there was an earlier period of low survivals, the recent declines could as easily be interpreted as part of a longer term regime shift pattern (Hare et al. 1998) rather than a novel response to current environmental conditions.

There are hints that the survival problem is "spreading" to freshwater, at least for steelhead. The Keogh River in B.C. first showed marine survival declines but in the last few

**Table 1.** Climate and smolt-to-adult survival ( $S$ ) of coho stocks for British Columbia in wet to dry regions and survival before 1988 compared with the last 5 years of returns.

Climate			
(month, year, days of rain (stations))	Region	Mean $S$ (%)	$S_{\text{recent}}/S_{\text{older}}$
3.3, 202 (Tofino)	WCVI	3.17	0.59
1.7, 190 (Agassiz)	LFR	6.51	0.53
1.1, 167 (Nanaimo)	ECVI	3.58	0.38
0.3, 102 (Kamloops)	UFR	2.14	0.41

**Note:**  $S_{\text{recent}}$ , average survival rate from 1989–1995;  $S_{\text{older}}$ , average survival rate from 1973–1988. Survival data from Simpson et al. (1997); climate data from Environment Canada ([www.cmc.ec.gc.ca/climate/normals/eprovwmo.htm](http://www.cmc.ec.gc.ca/climate/normals/eprovwmo.htm)).

years has also had very low egg-smolt survival rates (Fig. 2) that cannot be explained by any obvious changes in freshwater habitat conditions.

### The metabolic impairment hypothesis

Marine survival patterns as in Fig. 1 are usually assumed to reflect changes in marine environments (Beamish et al. 1997; Beamish and Bouillon 1995). However, the striking common denominator is not marine conditions but rather extended freshwater stream rearing. Further, differences associated with photoperiod and cloudiness suggest an atmospheric effect. Over a wide range of freshwater flow and thermal regimes, there is a striking correlation between the declines and temporal changes in indices of radiation (ozone depletion at ground level (Tarasick et al. 1996); UV-B penetration in freshwater lakes (Schindler et al. 1996)). A connection between radiation and survival would not be surprising, considering growing evidence of UV radiation impacts on aquatic productivity in general (e.g., Bothwell et al. 1994; Zagarese and Williamson 1994), as well as direct physiological effects on fish ranging from simple sunburn (McArdle and Bullock 1987) to suppression of immune responses (Salo et al. 1998) and egg mortality (Williamson et al. 1997). We can rule out the possibility that radiation impacts have been important but have acted through effects on productivity of marine-rearing environments; such effects should have had at least as much impact on chum, pink, and sockeye as on the stream-rearing species.

The metabolic impairment hypothesis is that increasing exposure to radiation during freshwater rearing first causes metabolic damage that results in increased mortality during the stressful period of smoltification, ocean migration, and adaptation to salt water. If this hypothesis is correct, what we measure as "marine" mortality is actually a symptom of exposure to stress during freshwater rearing. At higher dose levels, increasing metabolic effects should result in mortality in freshwater as well.

The only direct evidence we have of abnormal mortality during smolting is for coho in the Keogh River. Sawada (1993) found surprisingly high (up to 50%) mortality during migration from rearing sites to the river mouth; this mortality was independent of travel distance, hinting it was not related to cumulative exposure to factors such as predators.

Other mechanisms besides radiation damage could cause

delayed mortality in early ocean life following freshwater stress. Increased rearing temperatures, reduced insect food densities, etc., could result in juveniles having lower energy reserves for migration and marine predator avoidance. That is, there could be a whole syndrome of impacts due to changes in freshwater climatic factors. However, we can rule out the possibility that delayed mortality is due to general effects of degradation in freshwater-rearing habitats unrelated to particular factors like radiation; most of the declining trends in Fig. 1 are for hatchery stocks that are not subject to such effects (except during smolt migration from hatchery to sea).

If the metabolic impairment hypothesis is correct, marine survival rates will not recover even if ocean conditions return to "normal." However, there is some reason to hope for eventual recovery if the adults now surviving are treated as precious and are protected from harvesting and further habitat damage. There are species-specific differences in susceptibility to UV-B radiation (Blazer et al. 1997), indicating that natural selection on factors such as skin pigmentation can eventually result in fish better able to cope with current conditions.

### Tests that we pray will fail

There are at least two immediate ways for management agencies with hatchery and data resources to test the metabolic impairment hypothesis:

1. Experimental: Conduct paired comparisons, using hatchery stocks, of marine survival rates for fish reared with and without UV-B protection. This would require tagging and rearing large numbers of smolts for each treatment group and effective sampling of adult returns for tagged fish. It is well within the capability of B.C. hatchery programs considering the large number of fish already being tagged for catch composition and hatchery performance evaluations.
2. Comparative: Develop more detailed and extensive comparative studies using the variety of time series now being collected. Such comparisons should reveal spatial differences due to variation in factors that affect radiation exposure, such as dissolved organic matter concentration (DOC, humic acids, etc.) in rearing streams and also temporal variation correlated with indices of radiation loading (cloudiness, etc.). If we are correct that impacts are now starting to appear in freshwater, declines should be starting to appear in survival rates for stream-rearing life stages of non-anadromous populations. Declines should also be starting to appear in more northerly (e.g., Alaskan) populations, and these declines should be persistent.

Note here that we do not recommend detailed process research (radiation effects, etc.) as a high immediate priority; considering the many pathways through which effects could occur, such studies could neither prove nor disprove existence of an overall effect. However, there is one type of detailed study that could be worthwhile: a critical part of our argument is that marine survival effects should appear very shortly after ocean entry. All we know now is that fish enter the ocean and "soon" disappear, probably during the first summer-fall of ocean rearing. It may be possible in some

situations (e.g., Georgia Strait) to measure ocean dispersal and densities more accurately and hence determine whether the mortality is occurring as early as we suspect.

If the immediate tests do not fail, in the sense that strong radiation effects are found in the next few years, there will need to be some major changes in research priorities concerning the relationship between salmonids and the marine environment. In particular, studies will need to focus much more carefully on conditions faced by the fish during early ocean life, on the mechanisms of physiological damage, and on options for mitigating effects during freshwater rearing.

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