Canadian Nuclear Society
Waste Management, Decommissioning and Environmental Restoration
For Canada's Nuclear Activities: Current Practices and Future Needs
Ottawa, Ontario Canada May 8-11 2005

IMPACTS OF SPECIES INTRODUCTIONS ON THE HEALTH OF FISH COMMUNITIES RECEIVING CHRONIC RADIONUCLIDE EXPOSURES

[1] T.L. Yankovich, [2] J.M. Casselman and [3] R.J.J. Cornett

[1] Atomic Energy of Canada Limited, Chalk River, Ont. (yankovicht@aecl.ca).
[2] Lake Ontario Fisheries Assessment Unit, Ministry of Natural Resources, Glenora, Ont.
[3] Radiation Protection Bureau, Health Canada, Ottawa, Ont.

ABSTRACT

A study was conducted to evaluate the potential impacts of a northern pike introduction on the health of a fish community receiving chronic radionuclide exposure, primarily from ^{90}Sr. Overall, although significant changes occurred in the community composition and the health of fish populations following the pike introduction, these were not linked to radionuclide dose to fishes. This finding was further supported by assessing the health of forage fishes, which did not significantly change in the pre- versus post-pike fish communities and were comparable in condition to forage fishes inhabiting lakes with background radionuclide levels. Application of such resilient species as '*baseline organisms*' can provide a useful tool in the routine monitoring of ecosystems affected by multiple stressors.

I. INTRODUCTION

Ecosystems often consist of complex assemblages of interacting compartments that are potentially influenced by multiple stressors. These stressors can be physical, biological or chemical in nature, and can have additive or multiplicative effects, or in some cases, can have effects that counterbalance one another, resulting in no net change in ecosystem health. As a result, there is widespread interest in gaining better understanding of the relative influences of multiple stressors on aquatic ecosystem structure and function, in most cases, with the underlying goal of protecting ecological populations. Under conditions in which multiple stressors are acting in natural ecosystems, responses by resident species can vary as a function of organism resilience and tolerance to the complement of stressors that are acting in a natural system. As a result, interpretation of ecosystem health can be affected by the species being considered, possibly making some species better indicators of ecosystem health than others.

Changes in the fish length-to-weight relationships can provide critical information about the health and stability of fish populations.[1] Under extremely stressful conditions, healthy fish can begin to lose condition, exhibiting lower body mass-to-length relationships in response to stressors in their environments, where the condition of individual fish in a lake are thought to represent the overall health of the fish population.[2] Fish condition can represent a sensitive indicator of environmental stressors affecting food availability, such as changes in physico-chemical conditions to non-optimal values, shifts in the system prey base, increased predation and/or increased competition.[3] In addition, correlations between reduced condition and exposure to contaminants, including organic contaminants, heavy metals and to a lesser extent radionuclides, have been well documented.[4, 5, 6]

Similarly, the hepatosomatic index (HSI), a measure of the weight of hepatic (liver) tissue relative to the fresh weight of a fish, is positively correlated with contaminant exposure, but is expected to decrease in starved fishes.[3, 6, 7, 8] Therefore, comparison of temporal changes in somatic indices (such as condition factor) and visceral indices (such as the HSI) of health can be used to evaluate the impacts of different types of stressors, such as reduced food availability or contaminant exposure, on fish communities.

The objectives of this study were to quantify changes in fish community composition and size structure that occurred following the introduction of an efficient predator into a small, closed aquatic system; and to determine whether changes in fish condition factors (representing fish nutritional status) are correlated with the concentrations of key radionuclides in fish tissues for fishes occupying a lake receiving chronic, low-level inputs of radionuclides.

To address these objectives, work was conducted to assess changes in the fish community in Perch Lake on AECL's Chalk River Laboratories site. Perch Lake is a small, closed, littorally-dominated Canadian Shield lake that has been receiving chronic low-level inputs of radionuclides (^{90}Sr, HTO, ^{60}Co, ^{137}Cs) for a period of 40 to 50 years. In the mid- to late-1980s, Perch Lake experienced a northern pike introduction, which resulted in changes in community dynamics and predator-prey interrelationships in the lake. The potential impacts of the pike introduction relative to radionuclide exposure were compared.

II. STUDY DESIGN

II.A. Characterization of the Perch Lake Fish Community

The species composition and relative abundances of Perch Lake fishes were quantified between 1995 and 2003, and compared with a previous survey of the Perch Lake fish community that was conducted in 1980.[9] In addition, the current fish species composition was compared to anecdotal presence-absence data for fishes in the lake between 1958, 1973 and 1985, as well as in 1994.[9, 10] Fish specimens were weighed (in g fresh weight), and measured for snout to tail fin top length, bottom length and fork length (in mm). Fork length (FL) and fresh weight (FW) measurements from collected specimens were then used to calculate fish condition (K), where:

$$K = 10^5 \times [FW / FL^3] \qquad (1)$$

Total condition factors of Perch Lake fishes were compared to conditions of fishes collected from other CRL lakes with lower radionuclide levels, including Maskinonge Lake, Upper Bass Lake and Lower Bass Lake. A subset of fishes was dissected and characterized with respect to gender. In addition, fish hepatic tissues were extracted and weighed to estimate fish hepatosomatic indices (HSI). HSIs were determined for brown bullheads and northern pike to represent the impacts of the pike introduction on benthic and piscivorous fish species, respectively. Fishes were also qualitatively examined for general health, the presence of tumours, deformities, and occurrence of endo- and ecto-parasites in their soft tissues and on their exteriors, respectively.

II.B. Fish Condition and Radionuclide Transfer to Perch Lake Fishes

Temporal changes in doses to resident fish species were estimated over a period of 34 years using the approach that has been developed by FASSET, to provide information on radiological exposure conditions in Perch Lake in the pre-versus post-pike fish communities. Doses were then compared with a conservative criterion value of 0.6 mGy/d for fishes.[11, 12]

To test the relationship between radionuclide exposure and fish condition for different types of fish species, radionuclide levels were measured in fishes with a wide range of condition factors. Focus was placed on brown bullheads and northern pike, since no significant decline in condition was observed for other fish species occupying the lake. Specimens were chosen to represent fish size classes inhabiting the lake. Boneless hypaxial muscle was dissected from each fish and muscle tissue was dried at 70 ºC in a drying oven until no change in mass could be detected. Muscle tissue was then analyzed for ^{90}Sr, ^{60}Co and ^{137}Cs using beta- and gamma-spectroscopy, respectively. To test for changes in radionuclide transfer with differences in fish health, correlations were performed between fish condition, HSI and ^{90}Sr, ^{60}Co and ^{137}Cs activities in fish tissues.

III. STUDY FINDINGS

III.A. Characterization of the Perch Lake Fish Community

<u>Fish Species Composition</u>:

Comparison of fishes collected from Perch Lake in 1980 (prior to the pike introduction) and in the mid- to late-1990s (following the introduction) indicates that there have been shifts in the fish community composition and relative abundances of fishes inhabiting the lake (Figure 1). Prior to the pike introduction, yellow perch (*Perca flavescens*), pumpkinseeds (*Lepomis gibbosus*), brown bullheads (*Ameiurus nebulosus*), and six cyprinid species, including pearl dace (*Semotilus margarita*), bluntnose minnow (*Pimephales notatus*), creek chub (*Semotilus atromaculatus*), fathead minnow (*Pimephales promelas*), blacknose shiners (*Notropis heterolepis*), and lake chub (*Couesius plumbeus*), were present in Perch Lake.[9, 10] Yellow perch represented the most abundant fish species in the lake (with a percent abundance of approximately 58%), followed by pumpkinseeds (19%) and brown bullheads (17%).[9] Cyprinids were the least abundant type of fish, with percent abundances of approximately 6% in 1980. Northern pike were not present in Perch Lake during the 1980 fish survey.

In the 1990s, following the introduction of northern pike, the yellow perch population became virtually extirpated, and with the exception of one moderately-sized perch, only a few individuals of small body size remained in the lake.

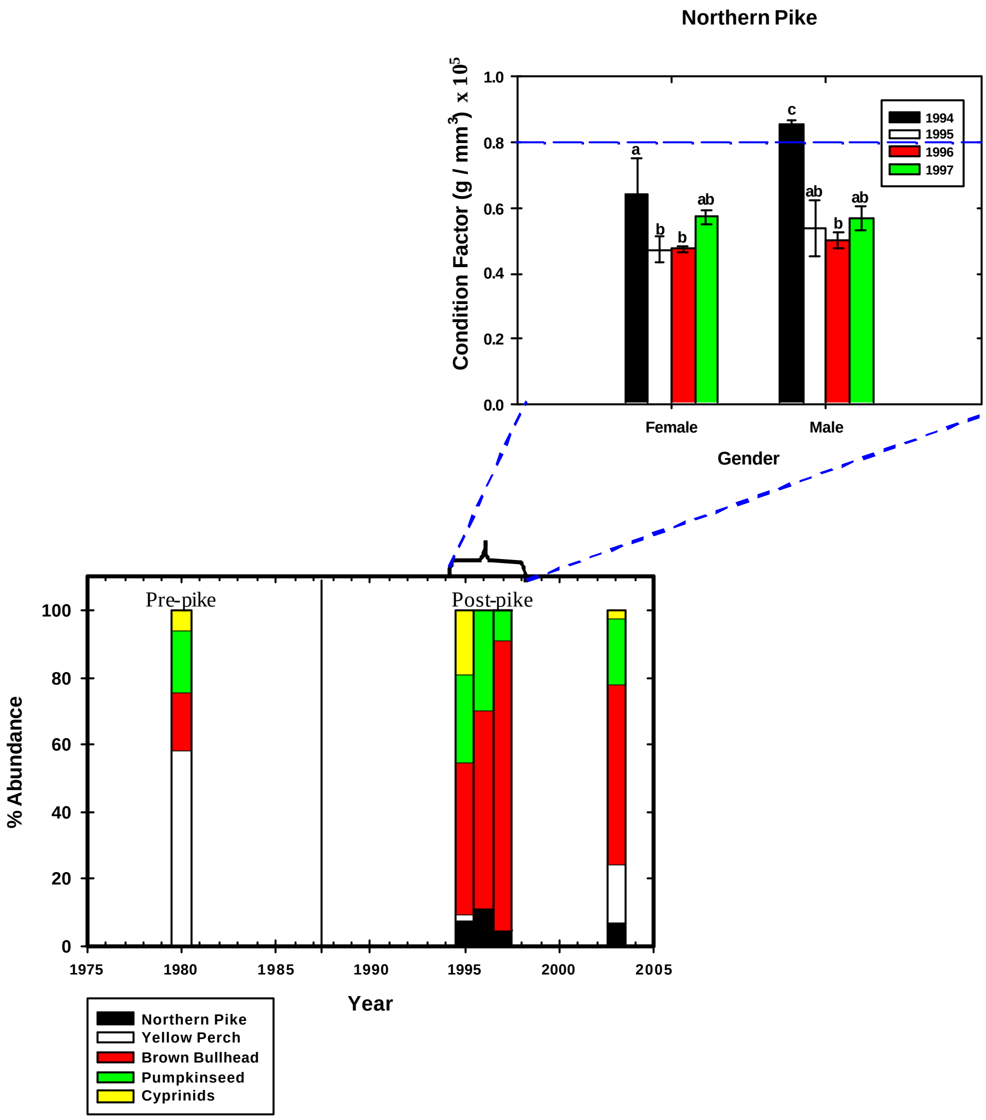

Figure 1: Changes in relative fish abundances in the pre- versus post-pike Perch Lake fish community. Blow-up compares changes in pike condition with gender in the mid- to late-1990s (dashed blue line represents typical pike condition).

Changes in the fish dynamics in the lake following the pike introduction also likely led to the great reductions or elimination of several forage species, such as lake chub (*Couesius plumbeus*), creek chub (*Semotilus atromaculatus*), bluntnose minnows (*Pimetheles notatus*), fathead minnows (*Pimetheles promelas*) and pearl dace (*Semotilus margarita*), all species that were once known to inhabit the lake.

In addition to the changes in the community composition and size distributions that occurred in Perch Lake following the pike introduction, changes in the relative abundances of key resident fish species also occurred. For example, brown bullhead densities increased from a pre-pike abundance of approximately 17% to a post-pike level of 83 to 88%, with a relatively higher proportion of small-bodied individuals than had been observed in the past and with numbers as high as 800,000 occurring in the lake in 1997 (Figure 1). These increases in the relative abundance of bullheads with small body sizes may be related to the occurrence of a strong bullhead year class due to decreased competition for prey, as other species, such as yellow perch, became depleted by the pike. Similar increases in bullhead densities have been reported in the literature following declines in percid species, with declines in bullhead condition being noted in some cases (South Dakota Statewide Fisheries Surveys 2102-F-21-R-35 and 2102-F21-R-35).

Fish Densities and Condition:

Bullhead densities in Perch Lake during the 1990s were much higher than typical for other lakes and rivers, in which the percent abundance of bullhead species often represents less than 5% of the fishes collected, with some lakes showing densities of up to approximately 15% relative to other fish species.[e.g. 13, 14] It is likely that the high bullhead densities in Perch Lake were contributing to the poor condition of the pike and bullheads occupying the lake, due to resource depletion. Typical condition factors of northern pike and brown bullheads are ≥ 0.8 and ≥ 1.3, respectively.[15] However, only approximately 20% of pike and 48% of bullheads examined from Perch Lake in the 1990s exhibited condition factors that fell within the typical ranges expected for these species.[16] This reduced condition is further confirmed by the corresponding declines in pike and bullhead HSI values, which is indicative of nutritional stress in fishes, as opposed to stress due to exposure to contaminants.[3, 6] By comparison, in most cases, pumpkinseed condition factors were comparable to or greater than those measured in other CRL lakes with background radionuclide levels during both 1980 and the mid-to-late 1990s (Figure 2).

Conditions of brown bullheads were higher prior to the pike introduction. In 1994, bullhead and pike condition factors remained comparable to pre-pike values, but declined in the years that followed during the 1990s. Such trends were pronounced in female fishes, which tended to lose condition faster than males, particularly for brown bullheads (Figure 1). Fish condition was likely being further impacted by the tendency of fishes to avoid consuming brown bullheads due to their spines.[17] It is expected that this tendency, in combination with the large densities of bullheads in Perch Lake, resulted in instability due to a disequilibrium in Perch Lake with respect to the energy distributions in the foodweb, where similar losses in pike condition to the point of starvation have been documented in Island Lake (Washburn County) due to non-optimal prey availability.[18] This likely created an interesting energetics problem in the Perch Lake system during the 1990s because bullheads represented greater than 80% of the total species abundance in the lake. As a result, bullheads could be viewed as an energy sink in Perch Lake, which was relatively inaccessible to other species. Pike and bullhead condition factors declined until they reached minimum values of 0.49 ± 0.03 and 0.77 ± 0.03 x 10^5 g/mm^3 (Figure 3). At these levels, fishes exhibited pronounced emaciation, with swollen caudal peduncles, sunken eyes, increased frequencies of empty gastrointestinal tracts, hardened gastrointestinal tract walls, discolouration and overall degradation of muscle, liver and other tissues, little to no visceral fat and resorption of gonadal tissues (particularly in females), suggesting that they had previously shown higher condition factors, but subsequently lost condition.

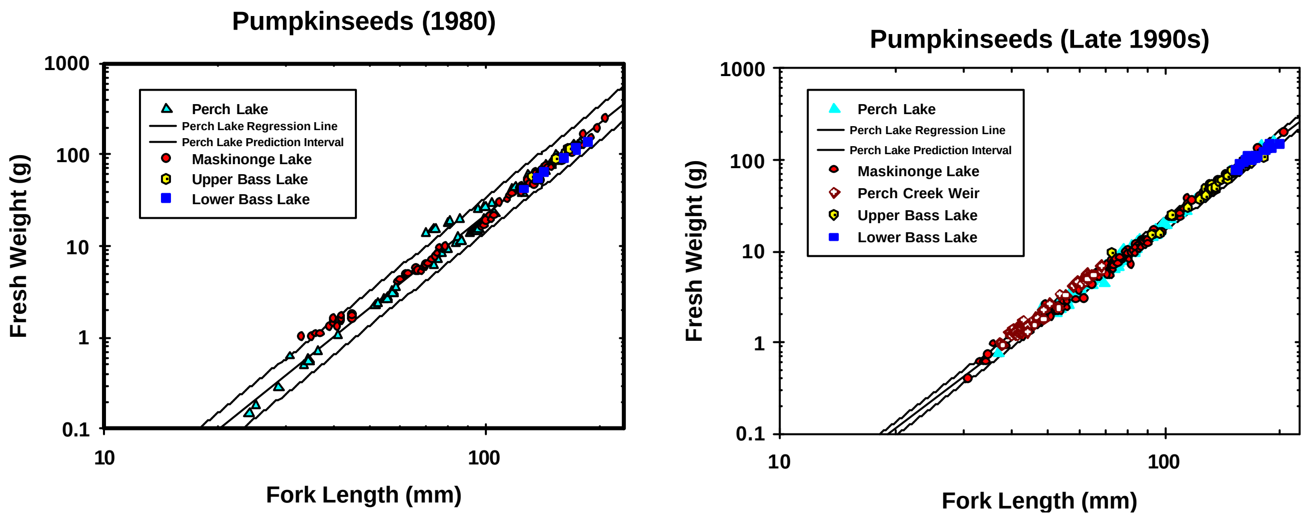

Figure 2: Fork length-to-fresh weight relationships for pumpkinseeds collected in CRL surface waters during 1980 and in the late 1990s. Lines on the each plot represent the Regression Lines, with the 95% Prediction Intervals, for Perch Lake pumpkinseeds on either side.

Therefore, in the past (when perch were still abundant), growth conditions were likely more favourable, but as food availability became less optimal, resident species began to lose condition. Again, decreases in fish condition and HSIs tended to be more pronounced in female fishes than in males (Figure 1), which is not surprising, due to the higher energetic requirements of females.[3] In addition, loss of condition appeared to occur more rapidly in pike than in brown bullheads, suggesting that bullheads may be more robust than pike. As benthivores, bullheads are feeding at the low end of the food chain, and the pike have removed most competitors for that resource, which could explain this trend.

Between 1996 and 1997, fish condition factors reached their minimum values. At this time, bullhead condition factors were as low as 0.77 x 10^5 g/mm^3, whereas those of pike were as low as 0.49 g/mm^3. Examination of stomach contents of pike and bullheads in 1996 indicated that these species were consuming large pike and bullheads, which would have been too large to consume if they had been alive. In addition, a number of dead bullheads were found floating in the lake during 1996. This suggests that a fish kill had occurred in 1996 and that the condition factors of pike and bullheads collected at this time were likely at or near the point of starvation for these species in natural ecosystems. This could be confirmed for pike, to some extent, through comparison of Perch Lake results with the starvation literature. Northern pike reportedly starved to death when a condition factor of 0.3 to 0.4 x 10^5 g/mm^{3}was reached during controlled starvation experiments that had been conducted under laboratory conditions.[3]

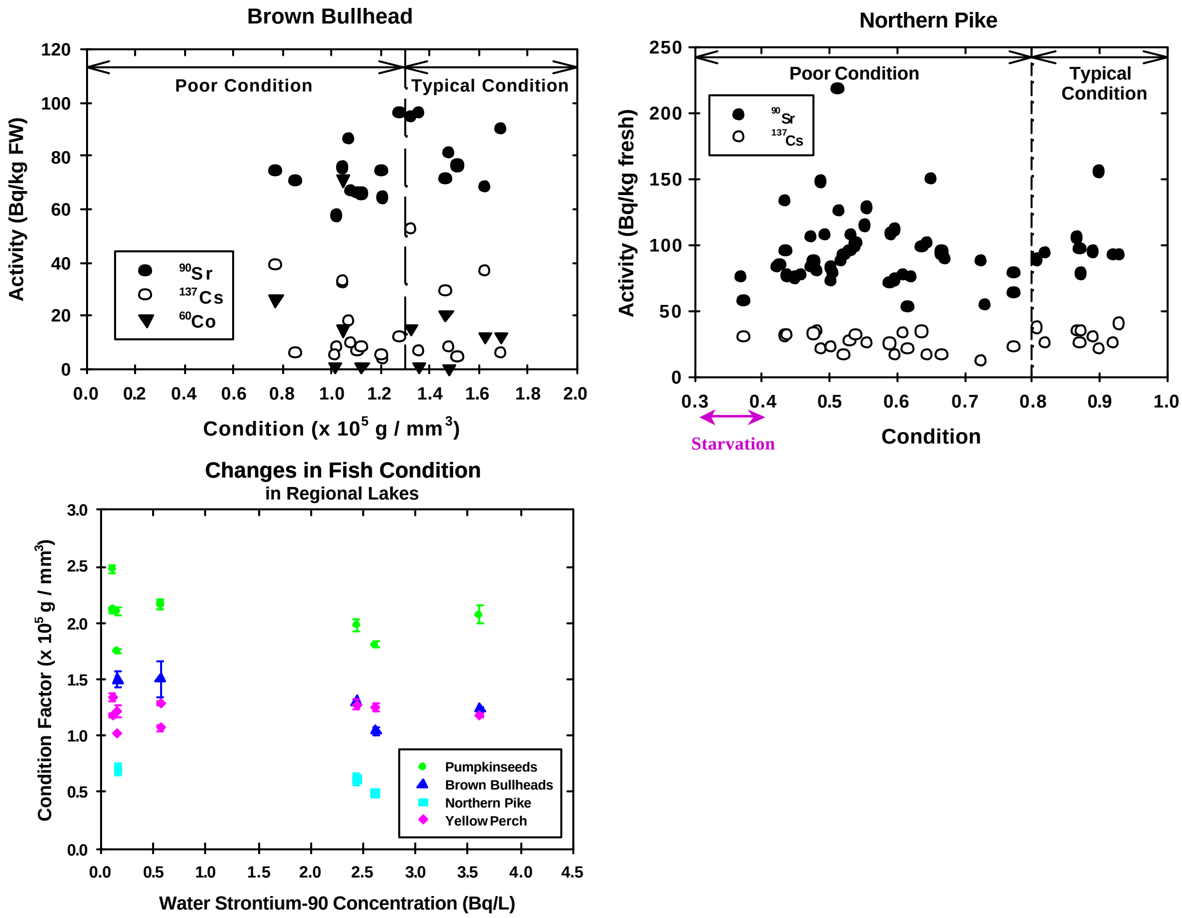

Figure 3: Comparison of radionuclide exposure to fishes from Perch Lake and other regional lakes relative to fish condition. Vertical groups of data in the third panel of the above figure represent data collected from Upper Bass Lake, Maskinonge Lake, Lower Bass Lake, Perch Lake (2003), Perch Lake (1998) and Perch Lake (1980), respectively.

Hepatosomatic Index (HSI):

The HSI of Perch Lake bullheads significantly declined with decreasing fish condition. These trends were observed for both female [HSI(F) = 0.0122 · Condition - 0.000267; $r^2 = 0.318$; $p < 0.001$] and male [HSI(M) = 0.00792 · Condition + 0.00426; $r^2 = 0.299$; $p < 0.001$] brown bullheads, where a stronger relationship existed for females. These changes in liver-to-whole body masses of brown bullheads relative to total condition were consistent with the expected symptoms of starvation.[8] Similar trends were also observed in female and male northern pike, where:

$$\text{HSI(F)} = 0.00908 \cdot \text{Condition} - 0.00107 \quad (r^2 = 0.448;\ p = 0.032) \qquad (2);$$

and

$$\text{HSI(M)} = 0.00624 \cdot \text{Condition} + 0.00151 \quad (r^2 = 0.576;\ p = 0.010) \qquad (3).$$

Unlike pike and bullheads, there was no relationship between HSI and female or male fish condition factor for pumpkinseeds (Linear regression; $p > 0.05$), suggesting that pumpkinseeds may not have been experiencing starvation.

III.B. Fish Condition and Radionuclide Transfer to Perch Lake Fishes

Relationships between radionuclide levels in fish muscle tissue and fish total condition factor were compared for northern pike and brown bullhead, which were the species that showed the widest range of condition, with some individuals showing the poorest condition. However, the poor condition factors observed in pike and bullheads from Perch Lake could not be accounted for by radionuclide concentrations present in these fishes. The mean ^{90}Sr activities of brown bullhead and northern pike were 76.4 ± 2.8 and 95.6 ± 3.7 Bq/kg fresh weight (FW), respectively, where condition factors of pike and bullhead were not significantly related to ^{90}Sr activities in the flesh (Figure 3; Linear Regression, $p > 0.05$). Similarly, no significant relationship existed between ^{137}Cs activity and fish condition for either species (Figure 3; Linear Regression, $p > 0.05$). The mean ^{137}Cs activity of brown bullhead (16.0 ± 3.2 Bq/kg FW; n = 21) was slightly lower than that of northern pike (26.8 ± 1.3 Bq/kg FW; n = 32).

In most cases, ^{60}Co was not detectable in the flesh of northern pike. As a result, there were inadequate data available to relate ^{60}Co activity with pike condition. However, brown bullheads contained measurable ^{60}Co activities, likely due to their benthivorous feeding mode.[17] The highest activities of ^{60}Co were measured in the sediments of Perch Lake, which contains approximately 98% of the inventory in the lake.[19]

Comparison of bullhead and pike condition factors relative to ^{90}Sr concentrations in CRL surface waters further supports the lack of a relationship between fish condition and radionuclide exposure, since no differences in fish condition were observed between lakes with varying radionuclide concentrations (Figure 3). In addition, condition factors of Perch Lake fishes were higher in 1980, although radionuclide levels in the lake and the corresponding dose to fishes were lower during the 1990s, further supporting the lack of a relationship between fish condition and radionuclide exposure (e.g. Figure 4).

IV. SUMMARY AND CONCLUSIONS

Comparison of fish health and radionuclide concentrations showed that no significant relationships existed between fish condition and radionuclide levels in fish tissues. Although radiological doses to fishes was historically higher in the lake, condition factors of Perch Lake fishes were significantly lower following the pike introduction. This suggests that exposure to radionuclides was not likely contributing to the poor condition observed for northern pike and brown bullheads in the mid- to late-1990s. Comparing changes in fish condition over time in Perch Lake further supports this conclusion. In general, condition factors of Perch Lake fishes that were measured in 1975 and 1980 (when radionuclide levels were higher in the lake), were either greater than or equal to those measured during the late 1990s and in 2003, despite the higher radionuclide levels predominating in the lake prior to the pike introduction.

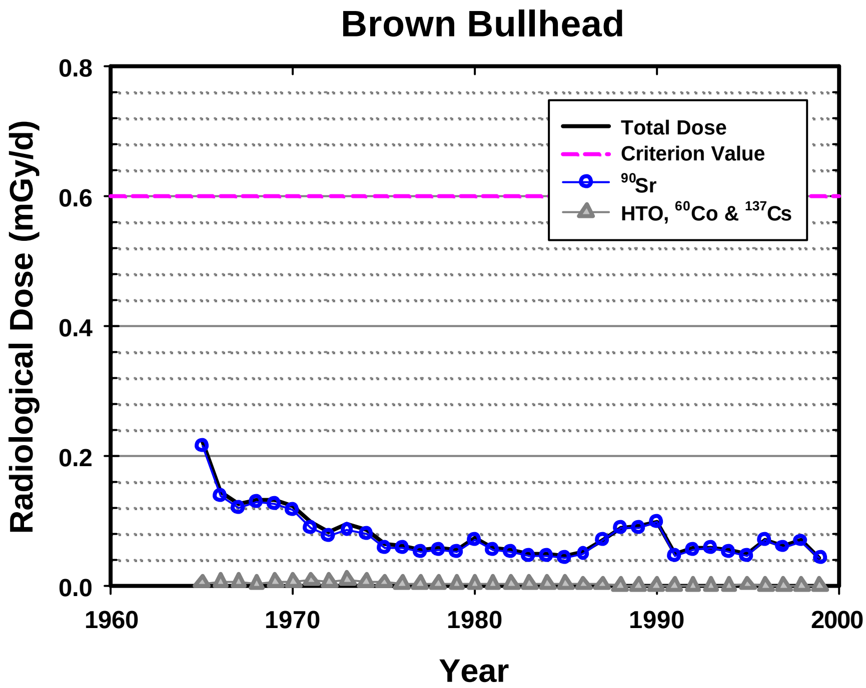

Figure 4: Temporal trends in dose to Perch Lake bullheads from key radionuclides. A conservative criterion value of 0.6 mGy/d for fishes is included for comparative purposes.[from 12]

Similarly, condition factors of Perch Lake fishes were comparable to or greater than those of fishes collected from other CRL lakes, which have much lower radionuclide levels. This suggests that fish condition was not being detrimentally influenced by radionuclide levels in the lake and concurs with findings that radionuclide levels in fishes and fish condition factor were not significantly correlated. Instead, it seems more likely that fish condition is being influenced by the energetic requirements of fish species. This conclusion is supported by comparing changes in fish condition relative to gender, where female fishes, which have higher energetic requirements, tended to lose condition more rapidly than did male fishes. In addition, the HSI, which tends to increase under contaminant exposure conditions and tends to decrease for fishes with poor nutritional statuses, was significantly lower in the post-pike Perch Lake fish community than in earlier years.

A summary of changes in health parameter response of Perch Lake fishes in the mid-to late-1990s, following the pike introduction, is provided in Table 1. Based on an examination of this table, all species did not appear to be influenced to the same extent following the pike introduction.

Table 1: Summary of responses of the Perch Lake fish community to the introduction of northern pike, based on historical data and field surveys conducted in the mid- to late-1990s.

Parameter	Parameter Response Following Pike Introduction				
	Cyprinids	*Pumpkinseeds*	*Brown Bullhead*	*Yellow Perch*	*Northern Pike*
Fish % Abundance	Declined with extirpation of some species.	No change.	Increased.	Declined.	Not applicable.
[a] Fish Total Length Range	Not studied.	No change.	No change.	Declined.	Not applicable.
Fish Total Length Distribution	Not studied.	Primarily small individuals.	Higher proportion of small individuals.	Primarily small individuals.	Not applicable.
Fish Condition Factor	Not studied.	Declined, but was comparable to conditions of pumpkinseeds from other CRL lakes.	Declined, with starvation and some mortality.	Inadequate data.	Initially high condition factor, which later declined, with starvation and some mortality.
Hepatosomatic Index (HSI)	Not studied.	No significant relationship exists between condition and HSI.	HSI increases with increasing condition.	Inadequate data.	HSI increases with increasing condition.

[a] Represents the difference between the maximum and minimum total length in mm.

For example, large differences in length ranges and abundances of pumpkinseeds did not occur in Perch Lake following the pike introduction, and any changes that did occur in pumpkinseed condition factors were comparable to those observed in other lakes on the CRL site (Figure 2). Similarly, unlike trends observed in pike and bullheads, hepatosomatic indices of pumpkinseeds showed no significant correlation with fish condition and that pumpkinseeds were not likely starving (since liver-to-body weight ratios and condition tend to decline in starving fish). In addition, the overall general health of pumpkinseeds was much better than observed for bullheads or northern pike. For example, tissues were healthy and not discoloured, visceral fat was present and gonadal resorption was not observed, further supporting the conclusion that pumpkinseeds may have been less affected by the changes in the Perch Lake fish community dynamics.

In general, large changes in fish community structure, with corresponding changes in fish health, occurred following the pike introduction. Several forage fish species were extirpated from the lake and densities of the past top predator, yellow perch, became greatly reduced, likely due to predation. The reduced perch numbers appeared to alleviate an ecological bottleneck, which resulted in significant increases in brown bullhead densities to levels that were much higher than observed in other water bodies under typical conditions. Corresponding changes in the health of the Perch Lake fish community could also be detected, particularly for females. Although predatory fish species were detrimentally affected by the pike introduction, the health of forage fish species, such as pumpkinseeds, did not appear to be greatly influenced, making it possible to assess temporal changes in ecosystem health using forage fishes as 'baseline organisms', since they did not respond to the stresses induced in post-pike fish community. This can be important in surface waters where long-term, routine environmental monitoring is being conducted, since monitoring of resilient, 'baseline organisms' facilitates assessment of temporal changes in biota exposure conditions, while removing the potential impacts of confounding stressors.

Overall, no clear relationships existed between Perch Lake fish community health and exposure to radionuclides in the lake (Figure 2).[16] In addition, reconstruction of radiological doses to fishes over a 40-year period indicated that, although peak doses to Perch Lake fishes occurred in the 1960s to mid-1970s, fish conditions in the pre-pike fish community were similar to or better than conditions of the same species inhabiting Perch Lake in the 1990s, as well as other Shield lakes with background levels of radionuclides for all species considered.

ACKNOWLEDGEMENTS

The authors would like to thank Atomic Energy of Canada Limited, the Lake Ontario Fisheries Assessment Unit and Trent University for providing the resources required to conduct this study.

REFERENCES

[1] T. Bolger and P. Connolly, "The Selection of Suitable Indices for the Measurement and Analysis of Fish Consumption", *J. Fish Biol.,* **34**, 171–182 (1989).

[2] D.J. Booth and J.A. Keast, "Growth Energy Partitioning by Juvenile Bluegill Sunfish, *Lepomis macrochirus* Rafinesque", *J. Fish Biol.,* **28**, 37-45 (1986).

[3] J.M. Casselman, Ph.D. Dissertation. University of Toronto (1978).

[4] A. Hontela, P. Dumont, D. Duclos and R. Fortin, "Endocrine and Metabolic Dysfunction in Yellow Perch, *Perca flavescens*, Exposed to Organic Contaminants and Heavy Metals in the St. Lawrence River", *Environ. Tox. & Chem*., **14**, 725-731 (1995).

[5] N. Le François, P. Blier, L. Adambounou and M. Lacroix,. "Exposures to Low-level Ionizing Radiation: Effects on Biochemical and Whole-body Indices of Growth in Juvenile Brook Charr (*Salvelinus fontinalis*)", *J. Exper. Zool.,* **283**, 315-325 (1999).

[6] M.Z. Vosyliene and N. Kazlauskiene, "Alterations in Fish Health State Parameters After Exposure to Different Stressors", *Acta Zoologica Lituanica, Hydrobiologia*, **9**, 83-94 (1999).

[7] Rios, "Changes in Metabolic Rate and Energy Reserve Utilisation during Starvation: Adaptations to Long-term Drought Periods", http://www-heb.pac.dfo-mpo.gc.ca/congress/2002/Tropical/Rios.pdf (2002).

[8] R.J. Strange, "Field Examination of Fishes", *In: Fisheries Techniques*, 2nd edition (B.R. Murphy and D.W. Willis, eds.), American Fisheries Society: Bethesda, Maryland, pp. 447- 482 (1996).

[9] T. Sowden and G. Power, 1981. "*The Icthyofauna of the Chalk River Property of Atomic Energy of Canada, Limited*", University of Waterloo, 158 pp (1981).

[10] MNR (Ministry of Natural Resources), "*Lake Survey Summary Report, District S6*", (1973).

[11] J. Brown, P. Strand, A. Hosseini and P. Børretzen, "Handbook for Assessment of the Exposure of Biota to Ionising Radiation from Radionuclides in the Environment", FASSET Deliverable 5 (2003).

[12] P. Thompson and G. Bird, "Biological Effects Benchmarks for the Protection of Aquatic Organisms against Radiation", IAEA-CN-109/88, 290-293 (2003).

[13] K. Underwood and J. Shields, "Lake Roosevelt Fisheries Monitoring Program: 1993 Annual Report", Dept of Natural Resources, Spokane Tribe of Indians, Wellpinit, WA, prepared for US-DOE (1993).

[14] Florida Lakewatch, "Long-term Fish Population Trends in Florida Lakes: 2001 Data", Department of Fisheries and Aquatic Sciences, University of Florida/Institute of Food and Agricultural Sciences (2001).

[15] K.D. Carlander, "*Handbook of Freshwater Fishery Biology*", The Iowa State University Press, Ames, Iowa (1969).

[16] T. Yankovich and R. Cornett, "Are the Condition and Health of Fish Populations Influenced by Exposure to Radioactive Contaminants?", *Proc. 1st Conf on the Impacts of Ionizing Radiation on the Environment*, Ottawa, Canada, 8 pp (2001).

[17] W.B. Scott and E.J. Crossman, "*Freshwater Fishes of Canada*", 2nd ed. Galt House Publications LTD, Oakville, Ontario (1998).

[18] T.L. Margenau, "Stunted Northern Pike: A Case History of Community Manipulations and Field Transfer", Wisconsin Department of Natural Resources, Research Report 169, June (1995).

[19] R.J. Cornett and I.L. Ophel, "Transport of ^{60}Co between Water and Sediments in a Small Shield Lake," *Can. J. Fish. Aquat. Sci.*, **43**, 877-884 (1986).